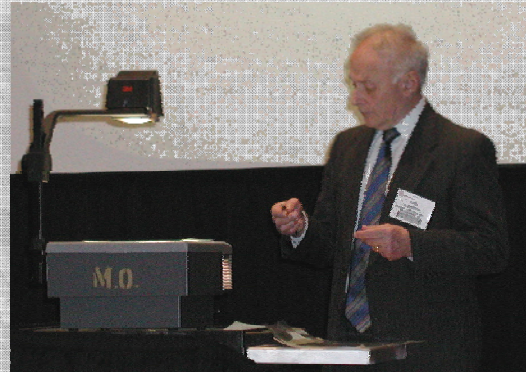


# **Professor Liviu Librescu Memorial Sessions at the ESM 2008 Mechanics Conference Virginia Tech, May 29-30, 2008**

**Professor Liviu Librescu**  
August 18, 1930 – April 16, 2007



## **Sessions Program and Booklet of Abstracts**

**Edited by**

**Pier Marzocca**  
**Clarkson University**

**and**

**Marek-Jerzy Pindera**  
**University of Virginia**





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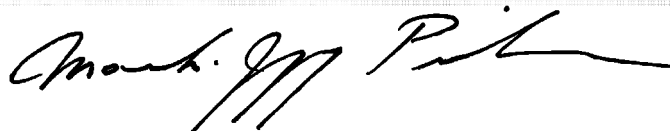


## Preface

When Mike Hyer of Virginia Tech and Carl Herakovich of the University of Virginia contacted us in January of 2008 about organizing sessions to commemorate Liviu Librescu's contributions to the science and technology of advanced materials at this Mechanics Conference, we were both delighted yet somewhat apprehensive about the task ahead. Both of us knew Liviu personally, and both of us were very familiar with the Engineering Science and Mechanics Department where our professional careers had begun. The tragedy that had occurred on April 16, 2007 that took Liviu's life among other victims had been particularly poignant because of our background.

We were delighted, indeed, that many colleagues and friends of Liviu's throughout the world, as well as others who did not know Liviu personally but who were influenced by his work, had accepted our invitations to contribute to the Liviu Librescu Memorial Sessions on such a short notice. This speaks volumes about the respect for Liviu as a scientist and as an extraordinary human being held by researchers throughout the world. We are grateful to you for participating and contributing to these memorial sessions, and we extend our warmest welcome to you at Virginia Tech, a place that we hold dear in our hearts.

We take this opportunity to express our deepest gratitude to Honorable Virgil Goode, the US Congress Representative from Virginia's 5<sup>th</sup> District, for his moral support of the Liviu Librescu Memorial Sessions. We are grateful.



Pier Marzocca and Marek-Jerzy Pindera  
Blacksburg, Virginia  
May 29, 2008



**Professor Liviu Librescu Memorial Sessions  
at the ESM 2008 Mechanics Conference  
Virginia Tech, May 29-30, 2008**

Distinguished scientists, distinguished lecturer to the Liviu Librescu Memorial,  
Dear friends,

I can honestly feel Liviu's sorrow for not being able to be here and participate at this prestigious scientific event and 100 year anniversary of ESM.

Who knows better than me, how much effort and hard work Liviu has devoted to such events in order to finally make it to the conferences, congresses, and be very well prepared to present and share as many as possible of his new results.

Not being allowed to participate in such events for many years while in Romania, upon his arrival in Israel at Tel Aviv University and afterwards in Blacksburg at Virginia Tech, Liviu has made it one of his top priorities to participate in as many scientific events that covered his topics of research. On many occasions I have heard colleagues and friend asking Liviu why he spends so much time preparing and participating in conferences. They were questioning if it won't be more beneficial for him to spend some of that time, for instance, on writing another books. I never heard Liviu answering to anyone regarding this, but once, I asked, since I was curious to understand as well. Liviu's interest to conferences and congresses was due to the interaction that such events presented. The feedback he received from the audience and the follow up discussions were his catalysts for future ideas and work. He told me that he is able to feel how the audience received his new results, when he present interesting results and when no.

Liviu always tried to bring new ideas and improve himself professionally at the same time. Right before April 16th 2007, Liviu was finalizing his presentations for the summer of 2007: for the AIAA SDM Conference in Hawaii, his Invited paper and the paper for the Symposium honoring Prof. Jozef Ignaczak at the Thermal Stresses Congress in Taipei, and a paper for a conference in Japan.

I would like to extend to all of you my gratitude for your commitment and time to honor in such a special way the memory of your teacher, advisor, colleague, collaborator, and friend and last but not least, my dearest husband and my best friend, Professor Liviu Librescu.

Liviu enjoyed life, had many planes to accomplished, was very devoted to his research, his students and his family. His last act, to sacrifice himself in order to give to the young students the opportunity to live gave to them the most prestigious lesson of his life. He shows the goodness that is present in the human race.

Thanks for having the opportunity to speak to you all, and please receive all my gratitude and best wishes for many accomplishments in all your endeavors,

Marilena Librescu



VIRGIL H. GOODE, JR.  
5TH DISTRICT, VIRGINIA

**Congress of the United States**  
**House of Representatives**  
Washington, DC 20515-4605

May 29, 2008

Dr. Ishwar Puri, Ph.D., Chairman  
Engineering Science and Mechanics Department (0219)  
Virginia Tech  
223 Norris Hall  
Blacksburg, VA 24061

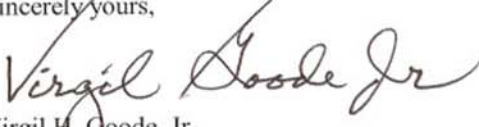
Dear Dr. Puri:

Please extend my appreciation to all who have gathered at the Mechanics Conference to honor Professor Liviu Librescu.

The Bible teaches that the greatest love a person can show is to lay down his life for a friend. Professor Librescu's brave actions in physically blocking the door to his classroom so that his students could escape the charging gunman demonstrated courage and selflessness that I suspect few others would muster.

Professor Librescu's life was devoted to research into numerous areas that is applied to enhance life as we know it. The results that his research produced will be integral in this century as science further develops a variety of structures and as flight, both in our atmosphere and in space, evolves. Throughout his career, and evident in his last act, Professor Librescu was devoted to the future, especially to the young persons whom he helped prepare to be tomorrow's leaders. While there is no explanation for the senseless tragedy that took Professor Librescu from our midst, his legacy lives in the product of his research and in the scores of students whom he inspired over the course of a lifetime, and for that we are blessed.

Sincerely yours,

  
Virgil H. Goode, Jr.

VHGjr/cld





March 30, 2008

Dr. Marek-Jerzy Pindera, University of Virginia; and  
Dr. Piergiorgio Marzocca, Clarkson University  
Livi Librescu Session Organizers  
The Mechanics Conference at Virginia Tech, May 29-30, 2008

*Re: Session in memory of Professor Livi Librescu at The Mechanics Conference*

Dear Professors Pindera and Marzocca:

Thank you for organizing a session in memory of Professor Livi Librescu at The Mechanics Conference that will be held at Virginia Tech from May 29-30, 2008 to mark the centennial of the Department of Engineering Science and Mechanics (ESM).

This session is a fitting tribute to the memory of Professor Librescu's heroic sacrifice on April 16, 2007. It is perhaps even more fitting that the session is being held during the ESM centennial year, since the history of our department and Professor Librescu's ultimate sacrifice are inextricably intertwined. Because of his actions, service to students is now indelibly etched in blood in the fabric and traditions of our department, and indeed in those of the institution. We are very fortunate that Dr. Librescu lent his name and distinction to ESM and Virginia Tech.

Professor Librescu was not only a brave man, he was also a high scholar of great international repute, a loving husband, a caring father, and a generous citizen of the world who endured many years of conflict and subjugation. His life offers many inspirational examples for us and future generations – through his survival during the Holocaust, his high and distinguished scholarship in Romania despite his struggle for freedom, his mentoring of scholars from around the world regardless of race, religion and national origin, and his remarkable and now immortalized concern for the welfare of students.

While we miss Professor Librescu's presence, the session that you have organized will allow us to celebrate his life and accomplishments, and also ensure that his memory will live on, as it should. The world owes an immeasurable debt of gratitude to Professor Librescu. Your efforts to honor his memory help redeem at least a small portion of that debt, and for this I am very grateful to you on behalf of our department.

Yours sincerely,



Ishwar K. Puri  
Professor and Department Head of Engineering Science and Mechanics

*Invent the Future*

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY  
*An equal opportunity, affirmative action institution*





**Professor Liviu Librescu**  
**(August 18, 1930 – April 16, 2007)**

We Remember.

We wish to pay tribute to the memory of Professor Liviu Librescu. Professor Librescu died in the senseless tragedy of Virginia Tech on April 16, 2007. He was a dedicated, caring and inspiring teacher, devoted to the education of his students and to the engineering profession, just for the love of it. He was always available to colleagues and students, and his last act was to give up his own life in order to save the lives of the students in his classroom. He had blocked the door with his body so that his students could escape.

Professor Librescu received many academic honors through the years, and was a well-respected scientist worldwide for his work in advanced structures, aerodynamics, aeroelasticity, and foundation of refined theories of laminated composite and sandwich structures, work that brought him academic prominence. His contributions to the engineering profession are countless, too many to list here. The scientists attending the ESM2008 Liviu Librescu Memorial Lectures will always remember him as one of the leaders in many research areas which include composite materials and structures, smart materials and structures, adaptive technologies for aircraft, rotorcraft and spacecraft systems, integrated advanced structures, control strategies, and structural optimization.

We all will remember him as a very knowledgeable scientist, enthusiastic and passionate about his research, professional and formal, striving always for perfection in research, and also in life. He was a true gentleman with a good sense of humor, humble in many situations and engineering forums. His fortitude and courage distinguished him until the very last moment, selfless to the end.

We will miss him greatly. Our prayers go out to his family, friends, students, and colleagues at Virginia Tech and throughout the world.

Pier Marzocca ([pmarzocca@clarkson.edu](mailto:pmarzocca@clarkson.edu))  
Liviu Librescu Session Organizer  
Clarkson University

and Marek-Jerzy Pindera ([mp3g@virginia.edu](mailto:mp3g@virginia.edu))  
Liviu Librescu Session Co-Organizer  
University of Virginia



## **Session # 1**

**29 May 2008, Thursday (8:00 – 9:45)**

Co-Chairs: **Z. Gürdal**, Delft University of Technology, The Netherlands, **P. Marzocca**, Clarkson University, USA

**8:00** – Opening: I.K. Puri (Virginia Tech, USA), P. Marzocca (Clarkson University, USA) and M.-J. Pindera (University of Virginia, USA)

**8:05** – **Fundamental Basic Research Issues in Structural Mechanics – An Air Force Office of Scientific Research Perspective**, Giurgiutiu V. (AFOSR, USA)

**8:25** – **Analysis of Variable Stiffness Panels Under Combined Mechanical and Thermal Loading**, Gurdal Z. and Abdalla M.M. (Delft University of Technology, THE NETHERLANDS)

**8:45** – **Recent Advances in Zigzag Methodology for Composite Beams and Plates**, Tessler A. (NASA Langley Research Center, USA), Di Sciuva M. and Gherlone M. (Politecnico di Torino, ITALY)

**9:05** – **Tailoring of Failure in Redundant Load Paths for Energy Dissipation – Potential and Challenge**, Dancila D.S. (Dancila LLC, USA), Armanios E. and Haynes R. (Georgia Institute of Technology, USA)

**9:25** – **Study on Singularities Interacting With Interfaces for a Thermoviscoelastic Trimaterial**, Chao C.K. (National Taiwan University of Science and Technology, TAIWAN)

**This session ends at 9:45 – Break (30 min)**

## **Session # 2**

**29 May 2008, Thursday (10:15 – 12:00)**

Co-Chairs: **R.T. Haftka**, University of Florida, Gainesville, FL, and **C. K. Chao**, National Taiwan University of Science and Technology, Taipei, Taiwan

**10:16** – **Vibration Control of a Cantilever Beam Using Piezoceramic Sensors and Actuators**, Spier C. and Bruch J.C. Jr. (University of California - Santa Barbara, USA)

**10:37** – **Pressure Pulse Tolerant Inflatable Structures**, Dancila D.S. (Dancila LLC, USA)

**10:58** – **Curved Laminae Equations for Hygrothermopiezoelectric Materials in Elastic Range**, Dökmeci M.C. (Istanbul Teknik Üniversitesi, TURKEY) and Altay G. (Bogazici University, TURKEY)

**11:19** – **Damping Changes in Initially Tensioned Composite Beams**, Kosmatka J.B. (University of California- San Diego, USA)

**11:40** – **Potential and Challenges of Bi-stable Composites for Wing Morphing**, Tawfik S. (Georgia Institute of Technology, USA), Dancila D.S. (Dancila LLC, USA) and Armanios E. (Georgia Institute of Technology, USA)

**This session ends at 12:00 – Lunch break (12:00 – 13:30)**



## **Session # 3**

**29 May 2008, Thursday (13:30 – 15:15)**

Co-Chairs: **J. G. Simmonds**, University of Virginia, Charlottesville, VA, and **Y. Morimoto**, Wakayama University, Wakayama, Japan

**13:31 – Re-Thinking the Kirchhoff Hypothesis: Down with Kinematics, Up with Constitution**, Simmonds J.G. (University of Virginia, USA)

**13:52 – Effects of the Transverse Core Compressibility in the Static and Dynamic Response of Sandwich Structures**, Hohe J. (Fraunhofer-Institut fuer Werkstoffmechanik, GERMANY)

**14:13 – Analysis of the Impact of a Thermo-Elastic Rod Against a Heated Wall Via D'Alembert Solution**, Rossikhin Y.A. and Shitkova M.V. (Voronezh State University, RUSSIA)

**14:34 – Shape and Deformation Measurements of Materials by Optical Methods**, Morimoto Y. and Fujigaki M. (Wakayama University, JAPAN)

**14:55 – Dynamic Response of a Timoshenko Type Thin-Walled Bar of Monosymmetrical Open Section Impacted by a Sphere**, Rossikhin Yu.A., Shitikova M.V. and Garifulin A.R. (Voronezh State University, RUSSIA)

**This session ends at 15:15 – Break (30 min)**

Note: Session # 4 has been omitted for consistency with the ESM2008 program

## **Session # 5**

**30 May 2008, Friday (8:00 – 9:45)**

Co-Chairs: **A. J. Levy**, Syracuse University, Syracuse, NY, and **M. Porfiri**, Polytechnic University, Brooklyn, NY

**8:01 – On the Spatial Behavior of Harmonic Vibrations in Linear Thermoelasticity**, Chirita S. (Al. I. Cuza University, ROMANIA)

**8:22 – Vibration Control of Piezo-Composite Beams: A Collaboration with Liviu I. Librescu**, Chandiramani N. K. (IIT-Bombay, INDIA)

**8:43 – Evaluation of Thermal Fracture Parameters for Inclined Cracks in Functionally Graded Materials using  $J_k$ -Integral**, Dag S. (Middle East Technical University, TURKEY) and Yildirim B. (Hacettepe University, TURKEY)

**9:04 – Mechanical Failure of Thin Films Bonded to Graded Substrates**, Guler M.A. (TOBB University of Economics and Technology, TURKEY)

**9:25 – Non-linear Aeroelasticity and Control of Lifting Surfaces: Liviu Librescu Tribute**, Marzocca P. (Clarkson University, USA)

**This session ends at 9:45 – Break (30 min)**



## **Session # 6**

**30 May 2008, Friday (10:15 – 12:00)**

Co-Chairs: **J. B. Kosmatka**, University of California San Diego, San Diego, CA, and **M.A. Guler**, TOBB University of Economics and Technology, Ankara, Turkey

**10:16 – Illustrating the Advantages of a Bayesian Over a Least Squares Approach to Material Properties Identification**, Gogu C., **Haftka R.T.** (University of Florida, USA), Le Riche R., Molimard J. and Vautrin A (Ecole des Mines de Saint Etienne, FRANCE)

**10:37 – High-Order Spectral Analysis to Investigate Non-linear M-DOF Structural Systems**, Nichols J. (NRL, USA), Milanese A. and **Marzocca P.** (Clarkson University, USA)

**10:58 – Mechanical Characterizations of Protein Crystal Structure**, **Park H.**, Yoon G., Eom K. and Na S.S. (Korea University, SOUTH KOREA)

**11:19 – Estimating the Covariance of Composite Properties with Measurement Uncertainty and Material Correlation Models**, Smarslok B.P., Haftka R.T. and Ifju P. (University of Florida, USA)

**11:40 – Thermal Effects of Ferro/Magnetic Materials Under Cyclic-Electric Loading**, **Yu S.** and Zhang L. (Tsinghua University, CHINA)

**This session ends at 12:00 – Lunch break (12:00 – 13:30)**

## **Session # 7**

**30 May 2008, Friday (13:30 – 15:15)**

Co-Chairs: **J. C. Bruch, Jr.**, University of California Santa Barbara, Santa Barbara, CA, and **S. Dag**, Middle East Technical University, Ankara, Turkey

**13:31 – Toughening of Silica Aerogels – Molecular Dynamics Simulations**, **Murillo J.S.R.** (West Virginia University), Bachlechner M.E. (Fairmont State University, USA), Barbero E.J. and Cairns D. (West Virginia University, USA)

**13:52 – Three-Dimensional Transient Analysis of Microelectromechanical Systems**, **Das K.** and Batra R.C. (Virginia Tech, USA)

**14:13 – Biomechanics of Epidermal Wound Closure in Embryos**, Wan F.Y.M. and **Sadovsky A.** (University of California-Irvine, USA)

**14:34 – A Mixture Theory Model of Ionic Polymer Metal Composites**, Del Bufalo G. (Polytechnic University, USA), Placidi L. (La Sapienza, ITALY) and **Porfiri M.** (Polytechnic University, USA)

**14:55 – Locally-Exact Homogenization Theory for Periodic Materials: Further Developments**, **Drago A.** and Pindera M.-J. (University of Virginia, USA)

**This session ends at 15:15 – Break (30 min)**



## **Session # 8**

**30 May 2008, Friday (15:45 – 17:55)**

Co-Chairs: **M.V. Shitikova**, Voronezh State University of Architecture and Civil Engineering, Voronezh, Russia, and **S. Chirita**, Al. I. Cuza University of Iasi, Iasi, Romania

**15:46 – Mechanical Modeling of Hollow-Particle Filled Composites**, Tagliavia G., Porfiri M. and Gupta N. (Polytechnic University, USA)

**16:07 – Antiplane Shear Problems for the Homogenized Fiber Composite with Nonlinear Interface**, Levy A.J. (Syracuse University, USA)

**16:28 – Parametric FVDAM vs FE Analysis of Multilayers with Wavy Architectures**, Khatam H. (University of Virginia, USA), Cavalcante M., Marques S. (University of Alagoas, BRAZIL) and Pindera M.-J. (University of Virginia, USA)

**16:49 – A Mixture Theory for Microstretch Thermo-Elastic Solids**, Gales C.B. (Al. I. Cuza University of Iasi, ROMANIA)

**17:10 – Generalized Solutions in Elasticity of Initially Stressed Materials with Voids**, Marin M. (University of Brasov, ROMANIA)

**17:35 – Thermal Distributions Around an Axisymmetric Insulated Barrier in a Non-homogeneous Semi-Infinite Medium**, Sahin A. (Fatih University, TURKEY)

**This session ends at 17:55**

## **Reserve Papers**

**TBA - Mathematical Modeling and Analysis of Magneto Thermo-elastic Plate**, Hasanyan D. (National Academy of Science, ARMENIA)

**TBA - Reflection and Refraction of Magnetoelastic waves at the Interface of Two Ferromagnetic Semi-Infinite Spaces**, Harutyunyan S., Reynolds W. T. Jr., Virginia Polytechnic Institute and State University, Blacksburg, VA and Hasanyan D.J., Armenia Academy of Science, Yerevan, Armenia



## Session # 1

**29 May 2008, Thursday (8:00 – 9:45)**

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**8:05** — **Fundamental Basic Research Issues in Structural Mechanics – An Air Force Office of Scientific Research Perspective**, Giurgiutiu V. (AFOSR, USA)

**8:25** — **Analysis of Variable Stiffness Panels Under Combined Mechanical and Thermal Loading**, Gürdal Z. and Abdalla M.M. (Delft University of Technology, THE NETHERLANDS)

**8:45** — **Recent Advances in Zigzag Methodology for Composite Beams and Plates**, Tessler A. (NASA Langley Research Center, USA), Di Sciuva M. and Gherlone M. (Politecnico di Torino, ITALY)

**9:05** — **Tailoring of Failure in Redundant Load Paths for Energy Dissipation – Potential and Challenge**, Dancila D.S. (Dancila LLC, USA), Armanios E. and Haynes R. (Georgia Institute of Technology, USA)

**9:25** — **Study on Singularities Interacting With Interfaces for a Thermoviscoelastic Trimaterial**, Chao C.K. (National Taiwan University of Science and Technology, TAIWAN)





## **FUNDAMENTAL BASIC RESEARCH ISSUES IN STRUCTURAL MECHANICS -- AN AIR FORCE OFFICE OF SCIENTIFIC RESEARCH PERSPECTIVE**

### **Victor Giurgiutiu**

Structural Mechanics Program Manager

Air Force Office of Scientific Research (AFOSR) Arlington, VA

The presentation will start with a historical perspective of the Air Force Office of Scientific Research (AFOSR) and the role it has played in funding and promoting fundamental basic research for the benefit of the Air Force and the US scientific community in general. Next, the presentation will offer a brief review of the current AFOSR organization and its research focus areas. Particular attention will be given to the field of Structural Mechanics, its current directions and the new challenges. The public-domain BAA-2008 and the AFOSR public website will be used as reference materials. Administrative aspects such as the funding cycle, the white-paper and proposal submission time lines, and the proposal review process will also be addressed.

The presentation is conceived as a dialog with the audience: the brief presentation from the author will be followed by an interactive questions and answers period.

### **Brief Vita:**

Education: Imperial College, London, UK: PhD (1977) Aeronautical Structures; BS (1972) Aeronautics.

Research: Adaptive Materials and Smart Structures, Structural Health Monitoring, Mechatronics; Embedded Ultrasonic NDE with Piezoelectric Wafer Active Sensors (PWAS); Active Biomedical Sensors, Integrated Nano Sensors.

Employment: 1996-current: University of South Carolina, Professor of Mechanical Engineering (2005) and Director of the Laboratory for Adaptive Materials and Smart Structures. 1992-1996: Virginia Tech, ESM and Center for Intelligent Materials Systems and Structures. 1977-1992:

Aviation Research Institute, Bucharest, Romania.

Service: Associate Editor of Structural Health Monitoring - An International Journal (Sage Pub.); chair of the Structural Health Monitoring Person of the Year committee, guest editor for Journal of Intelligent Material, Systems and Structures, and Smart Structures and Systems - An International Journal, organizer, chair/co-chair of numerous conferences in smart structures, adaptive materials, structural health monitoring, etc.

Currently, the author serves a 2-year assignment as program manager for Structural Mechanics at the Air Force Office of Scientific Research

([http://www.afosr.af.mil/ResearchAreas/research\\_aero\\_structural.htm](http://www.afosr.af.mil/ResearchAreas/research_aero_structural.htm))

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## **ANALYSIS OF VARIABLE STIFFNESS PANELS UNDER COMBINED MECHANICAL AND THERMAL LOADING**

**Mostafa M. Abdalla and Zafer Gürdal**

Faculty of Aerospace Engineering  
Delft University of Technology

In contrast to the classical stacking sequence design of composite laminates with constant ply angles over the entire layer, each ply can be designed with spatially varying optimal fibre orientation angle resulting in variation of the stiffness properties over the structure. Such laminates are often denoted as 'variable-stiffness panels' in the literature [1,2]. By allowing the stiffness properties of fibre-reinforced composites to vary from one point to another, the design space is significantly expanded as compared to the classical stacking sequence design problem, therefore opening the possibility for substantially improved designs for the same weight.

Because the spatial variability of the fibre angles, which also influences the coefficient of thermal expansion as well as the stiffness properties, the response of variable stiffness panels to thermal loads can be quite complex. Given that thermo-set composite panels are usually cured at elevated temperatures, which cause cross-linking of the polymer chains, there will be residual stresses at room temperature after cure. For traditional straight fiber panels such stresses could be uniform over the panel and can be taken into account easily. For variable stiffness panels, the residual stresses will also be changing spatially over the panel platform, and can be quite unintuitive. The resulting thermal stresses can also have a significant effect on the strength and buckling performance of such panels, and these effects might be unintuitive as well. The proposed paper investigates the effect of considering nonuniform thermal loads in combination with mechanical loads on the performance of variable stiffness panels. Panel performance is measured by its in-plane stiffness and first buckling load. The trade-off curves between stiffness and buckling load are drawn for different levels of thermal loading. To simplify the presentation, only linear fiber angle variation is considered.

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## RECENT ADVANCES IN ZIGZAG METHODOLOGY FOR COMPOSITE BEAMS AND PLATES

Alexander Tessler<sup>1</sup>, Marco Di Sciuva<sup>2</sup>, and Marco Gherlone<sup>2</sup>

<sup>1</sup>NASA Langley Research Center, Hampton, Virginia

<sup>2</sup>Department of Aeronautics and Space Engineering, Politecnico di Torino, Torino, Italy

The development of laminated-composite structures as the primary load-bearing components of a vehicle, that are efficient and reliable, requires significant advancements in stress analysis and failure prediction methodologies. The ongoing quest for laminated-composite beam, plate, and shell theories with superior predictive capabilities has led to the development of a variety of refined theories, many of which are computationally prohibitive or have significant flaws in their theoretical foundation or predictive capability. These drawbacks have suppressed the acceptance of many such theories for stress analyses in a design setting. One class of theories that has emerged as practical for engineering applications is known as *zigzag* theories. Studies have shown that these theories provide response predictions that are sufficiently accurate for engineering design and that are comparable to those of computationally demanding and relatively complex layer-wise and higher-order theories. This presentation will focus on the recent *zigzag*-theory contribution in [1], where the authors have elucidated the serious shortcomings of the most notable *zigzag* theories that have remained unresolved for over two decades. They have also provided a means for advancing this class of theories that is expected to be significantly more attractive to engineering practitioners. The authors have overcome the fundamental theoretical drawbacks of the previous theories in an original manner and have rigorously explained the causes of these difficulties. The new *zigzag* theory formulated for beams that exhibit a high degree of transverse shear flexibility has been developed based upon several original ideas. Specifically, the kinematic assumptions employ a novel  $C^0$ -continuous (across lamina interfaces) representation of the displacement field that is independent of the number of material layers and does not require enforcement of transverse-shear-stress continuity to yield accurate results. Unlike other similar theories, the *zigzag* contribution to the displacement field is zero-valued at the top and bottom surfaces of a beam, which is physically realistic. Additionally, the force equilibrium equations, constitutive equations, boundary conditions, and strain-displacement relations are completely consistent, with respect to the virtual work principle, and a transverse-shear correction factor is not required. This new theory is devoid of a major shortcoming of other similar theories; that is, the new theory enables accurate modeling of the clamped boundary condition while adhering strictly to the variational requirements. The new *zigzag* theory is better suited for engineering practice than previous theories because of its complete theoretical consistency, relative simplicity, and its ability to model accurately the transverse shear and axial deformations of the individual layers in a physically realistic manner. Importantly, the theory is amenable to the development of computationally efficient  $C^0$ -continuous (across element interfaces) finite elements that can be implemented into general purpose codes and thus can be used, with relative ease, to design an important class of high-performance aerospace structures. Moreover, the methodology in [1] is readily extendable to laminated-composite plate and shell models. Results have been obtained for a wide range of important problem parameters, including for beam problems that are extremely difficult for other beam theories to model accurately. The results clearly demonstrate the range of validity of the theory and establish the technical contribution. With a wider acceptance of a properly formulated *zigzag* theory, such as the one presented by the authors, advancements in design technology that contribute to improved aerospace vehicles and increased success of future NASA missions are expected.

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## TAILORING OF FAILURE IN REDUNDANT LOAD PATHS FOR ENERGY DISSIPATION – POTENTIAL AND CHALLENGES

**D. Stefan Dancila<sup>1</sup>, Erian Armanios<sup>2</sup>, and Robert Haynes<sup>3</sup>**

<sup>1</sup> Managing Member and Chief Scientist, Dancila LLC, Marietta, GA 30066.

<sup>2</sup> Professor, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150.

<sup>3</sup> Graduate Research Assistant, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150.

A patented failure tailoring concept generating a yield type response and increased energy dissipation in tension loaded 1D structures (e.g. tethers, straps, ropes, etc.) (Fig. 1) has been proposed, modeled, and experimentally verified by two of the authors (Refs. 1-4). The concept relies upon the redistribution of load among a network of redundant load paths elements of tailored strength and length, as well as upon the naturally occurring distribution of strength among nominally identical structural elements in order to induce a sequential, progressive failure process resulting in increased fracture surface area. While not limited to composite material construction, this failure tailoring concept can advantageously benefit from the high specific strength and stiffness typical of high performance fibers and elastomeric matrices. Potential applications of the concept have been proposed and investigated (Refs. 5-6). Current research efforts are aimed at characterizing a generalized form of the tailoring concept via analytical modeling and experiment. The presentation will provide insight into the potential of this generalized form and into the challenges that need to be overcome on the path towards practical implementation.

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6. D. S. Dancila, "Pressure Pulse Tolerant Inflatable Space Structures," Inflatable Space Structures Forum, 41<sup>st</sup> AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials (SDM) Conference, Atlanta, April 3-6, 2000.

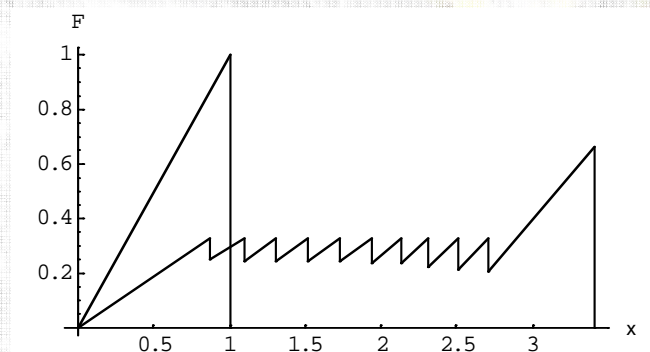


Figure 1. Comparison of normalized tensile response of conventional and tailored structures



## **STUDY ON SINGULARITIES INTERACTING WITH INTERFACES FOR A THERMO-VISCOELASTIC TRIMATERIAL**

**C. K. Chao**

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A general solution for a thermoviscoelastic trimaterial combined with a point heat source and a point heat sink is presented in this work. Based on the method of analytic continuation associated with the alternation technique, the solutions to the heat conduction and thermoelastic problems for three dissimilar, sandwiched media are derived. A rapidly convergent series solution for both the temperature and stress field, expressed in terms of an explicit general term of the corresponding homogeneous potential, is obtained in an elegant form. The hereditary integral in conjunction with the Kelvin-Maxwell model is applied to simulate the thermoviscoelastic properties, while a thermorheologically simple material is considered. Based on the correspondence principle, the Laplace transformed thermoviscoelastic solution is directly determined from the corresponding thermoelastic one. The real time solution can then be solved numerically by taking the inverse Laplace transform. A typical example concerning the interfacial stresses generated from a combined arrangement of a heat source and sink are discussed in detail. The corresponding thin film problem is also discussed.



## Session # 2

**29 May 2008, Thursday (10:15 – 12:00)**

Co-Chairs: **R.T. Haftka**, University of Florida, Gainesville, FL, and **C. K. Chao**, National Taiwan University of Science and Technology, Taipei, Taiwan

**10:16 – Vibration Control of a Cantilever Beam Using Piezoceramic Sensors and Actuators**, Spier C. and **Bruch J.C. Jr.** (University of California - Santa Barbara, USA)

**10:37 – Pressure Pulse Tolerant Inflatable Structures**, **Dancila D.S.** (Dancila LLC, USA)

**10:58 – Curved Laminae Equations for Hygrothermopiezoelectric Materials in Elastic Range**, **Dökmeci M.C.** (Istanbul Teknik Universitesi, TURKEY) and **Altay G.** (Bogazici University, TURKEY)

**11:19 – Damping Changes in Initially Tensioned Composite Beams**, **Kosmatka J.B.** (University of California- San Diego, USA)

**11:40 – Potential and Challenges of Bi-stable Composites for Wing Morphing**, **Tawfik S.** (Georgia Institute of Technology, USA), **Dancila D.S.** (Dancila LLC, USA) and **Armanios E.** (Georgia Institute of Technology, USA)





## VIBRATION CONTROL OF A CANTILEVER BEAM USING PIEZOCERAMIC SENSORS AND ACTUATORS

C. Spier<sup>1</sup> and J. C. Bruch, Jr.<sup>1,2</sup>

<sup>1</sup>Department of Mechanical Engineering, University of California, Santa Barbara, CA

<sup>2</sup>Department of Mathematics, University of California, Santa Barbara, CA

Active vibration control is implemented using a piezoceramic actuator and sensor bonded to the top and bottom surfaces of a cantilever beam. The control is exercised using closed-loop displacement feedback. An efficient analytical method is developed for finding the eigenfunctions and eigenfrequencies for this nonstandard eigenvalue problem. The basic formulation of the problem is given in terms of a nonstandard differential equation containing distributions and their derivatives which is converted to an equivalent integral equation formulation by introducing an explicit Green's function. After approximating the kernel of the integral equation in terms of Fourier series based on the eigenfunctions of the standard uncontrolled cantilever beam differential equation, a method of solution is outlined which consists of expressing the integral equation as an infinite series of linear equations and using a finite number of these equations in the numerical solution. The proposed integral approach is demonstrated by applying it to the piezoceramic patch vibration control of the cantilever beam. Numerical solutions are obtained to generate the eigenfunctions (mode shapes) and eigenfrequencies (natural frequencies) of the beam. These analytical results are used to check a finite element code that was written for this problem. The results compare very favorably for the first three modes. A discussion will also be presented using closed-loop velocity feedback control.



## PRESSURE PULSE TOLERANT INFLATABLE STRUCTURES

### D. Stefan Dancila

Managing Member and Chief Scientist, Dancila LLC, Marietta, GA 30066.

Inflatable structures rely upon the stiffening effect of internal pressurization on a membrane type envelope to provide structural solutions for large size and/or volume structures of reduced weight. The range of applications includes terrestrial habitats, balloons, non-rigid airships (blimps), as well as existing and proposed space and/or planetary habitats and large space reflectors. Motivated by potential weight savings, relative ease of deployment and typically large expanded vs. launch size ratios, a significant amount of research interest has been devoted in recent years to the study of inflatable space structures. Technological developments in materials as well as the desire for large size, geometrically accurate electromagnetic wave reflectors for space applications<sup>1-3</sup> provided the impetus for revisiting this structural concept<sup>4</sup>. An alternate application of inflatable space structures consists in the creation of large volume, inhabitable, flexible chambers for use in conjunction with space stations (e.g. NASA's TransHab) or planetary bases<sup>5</sup>. Ref. 6 provides a general overview of the state of the art and of technological needs for large space structures, with inflatable space structures addressed as a subset. In conjunction with the use of inflatable space structures as inhabitable chambers a safety concern can be raised regarding structural response to an accidental internal pressure pulse, since wall failure would lead to a rapid depressurization and loss of life-supporting capacity.

This work evaluates the applicability and benefits of a structural tailoring concept for flexible composite materials<sup>7-8</sup>, characterized by yield-type response under tensile loading, when applied to the problem of an inflatable space structure loaded by an accidental internal pressure pulse<sup>9</sup>.

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## CURVED LAMINAE EQUATIONS FOR HYGROTHERMOPIEZOELECTRIC MATERIALS AT ELASTIC RANGE\*

M. Cengiz Dökmeci<sup>1</sup> and Gülay Altay<sup>2</sup>

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<sup>2</sup> Department of Civil Engineering & Kandilli Observatory and Earthquake Research Institute, Boğaziçi University, Çengelköy, 34684 Istanbul, Turkey; ([askarg@boun.edu.tr](mailto:askarg@boun.edu.tr))

This study presents the system of two-dimensional equations governing the dynamic problems of a curved, hygrothermopiezoelectric laminae at the elastic range. The laminae is functionally graded across its thickness, and it may comprise any number of perfectly bonded layers, each with a distinct but uniform thickness, curvature and physical properties. In the first part of the study, the three-dimensional fundamental elastic equations of hygrothermopiezoelectric materials are expressed in differential form, and also, in variational form through a generalised variational principle. The principle is formulated most recently for smart elastic laminae. In the second part, by use of the variational principle, the system of approximate governing equations of the laminae is systematically deduced from the three-dimensional equations in both invariant, differential and variational forms for the case when the mechanical displacement, electric potential, temperature increment and moisture concentration vary linearly across the laminae thickness. All the mechanical, electrical, and hygrothermal effects between the layers of the laminae are taken into account. The system of two-dimensional equations governs the thickness-shear, extensional, and flexural motions of the laminae. In the third part, emphasis is placed on special material, motions and geometry of the laminae. In particular, the governing equations of plane laminae and laminated beams are recorded and a numerical algorithm is indicated for the problems.

\* Work supported in part by TUBA.

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## DAMPING CHANGES IN INITIALLY TENSIONED COMPOSITE BEAMS

**John B. Kosmatka**

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It is well known that applying an axial tension force will stiffen a beam column and increase the bending vibration frequencies, where this effect is much more pronounced in the fundamental bending modes. Moreover, the application of a compressive force lowers the bending stiffness and the corresponding bending vibration frequencies, where the natural frequency approaches zero at buckling. While numerous researchers have studied the change in the beam vibrations with axial load, there are no published studies that investigate the modal damping with axial load.

In the current paper, the damping response of a beam subjected to an initial axial force is studied both analytically and experimentally. In the analytical development, closed-form solutions are developed for the damping coefficient of an axially loaded beam. It is shown that the modal damping varies as a result of mode number and applied axial load. Applying a tension load to the beam will increase beam bending stiffness and lower the modal damping ratio, where this damping reduction is greatest for the fundamental mode, especially when the tension load is much greater than the absolute magnitude of the buckling load. This is common for spinning fan or propeller blades, where the spin produced centrifugal forces can result in tension loads over 10-200 times greater than the absolute magnitude of the buckling load. Applying a compression load will decrease the beam bending stiffness and increase the modal damping ratios tremendously for the lower modes as the applied load approaches the buckling load. In the experimental investigation, two different composite (graphite/epoxy) beams are loaded in an MTS axial test machine and then modal tested using an impact hammer and an attached accelerometer. Experimental results agree with the aforementioned analytical results showing that the application of a tension load raises the beam undamped natural frequency and lowers the corresponding modal damping. Moreover, the application of a compression load clearly lowers the beam undamped natural frequency, but significant raises the corresponding modal damping.



## POTENTIAL AND CHALLENGES OF BI-STABLE COMPOSITES FOR WING MORPHING

**Samer Tawfik<sup>1</sup>, D. Stefan Dancila<sup>2</sup>, and Erian Armanios<sup>3</sup>**

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<sup>2</sup> Managing Member and Chief Scientist, Dancila LLC, Marietta, GA 30066.

<sup>3</sup> Professor, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0150.

The focus of the current research is to investigate the potential of using bi-stable composites for wing morphing. It is essential to define the design space for laminated composites exhibiting bi-stable behavior and identify the key parameters controlling their behavior. For this purpose a nonlinear Finite Element (FE) methodology using ABAQUS<sup>TM</sup> code is developed to predict both the cured shapes and the stability characteristics of unsymmetric cross-ply laminates [1, 2]. In addition, experimental efforts are performed to develop comparisons with test data to validate the analytically predicted results [1-3].

Isolation of the controlling parameters for bi-stable behavior enables a rigorous selection of the actuation technique [4]. In this regard a manufacturing method is suggested for attaching piezoelectric actuators to a bi-stable panel to serve two purposes. Namely, conserving the favorable stability characteristics of the bi-stable panel and optimizing the actuator performance. The developed nonlinear FE methodology is extended to predict actuation requirements of bi-stable panels. Accordingly, a morphing bi-stable panel is manufactured and tested. Actuator requirements, predicted using the nonlinear FE analysis, are found to be in agreement with the test results. The current research suggests wings for an Uninhibited Aerial Vehicle (UAV) as a potential application of bi-stable panels. To this end a set of bi-stable panels is manufactured by combining symmetric and unsymmetric balanced and unbalanced stacking sequence and their stability characteristics are predicted [5]. A preliminary analysis of the aerodynamic characteristics of the manufactured panels is carried out using Athena Vortex-Lattice (AVL) code [6]. Based on the results of the preliminary study evidential aerodynamic benefits of the manufactured bi-stable panel are provided.

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## **Session # 3**

**29 May 2008, Thursday (13:30 – 15:15)**

Co-Chairs: **J. G. Simmonds**, University of Virginia, Charlottesville, VA, and **Y. Morimoto**, Wakayama University, Wakayama, Japan

**13:31 – Re-Thinking the Kirchhoff Hypothesis: Down with Kinematics, Up with Constitution, Simmonds J.G.** (University of Virginia, USA)

**13:52 – Effects of the Transverse Core Compressibility in the Static and Dynamic Response of Sandwich Structures, Hohe J.** (Fraunhofer-Institut fuer Werkstoffmechanik, GERMANY)

**14:13 – Analysis of the Impact of a Thermo-Elastic Rod Against a Heated Wall Via D'Alembert Solution, Rossikhin Y.A. and Shitikova M.V.** (Voronezh State University, RUSSIA)

**14:34 – Shape and Deformation Measurements of Materials by Optical Methods, Morimoto Y.** and Fujigaki M. (Wakayama University, JAPAN)

**14:55 – Dynamic Response of a Timoshenko Type Thin-Walled Bar of Monosymmetrical Open Section Impacted by a Sphere, Rossikhin Yu.A., Shitikova M.V. and Garifulin A.R.** (Voronezh State University, RUSSIA)





## RE-THINKING THE KIRCHHOFF HYPOTHESIS: DOWN WITH KINEMATICS, UP WITH CONSTITUTION

**James G. Simmonds**

Department of Civil Engineering, University of Virginia, Charlottesville, USA

It is argued that the classical *kinematic Kirchhoff Hypothesis* that *normal fibers deform into normal fibers without extension* is physically questionable, unnecessary, and may lead to ill conditioning. Rather, it is claimed the governing equations of both linear and nonlinear theories of beams, plates, and shells, including inertial and thermal effects, may be formulated so that approximations occur only in the constitutive relations. This is logically satisfying because these rest, ultimately, on inexact experiments. By means of a Legendre-Fenchel transformation, the standard strain- plus kinetic-energy density  $\epsilon$  is recast into a mixed form  $\psi$  into which the *constitutive Kirchhoff Hypothesis* may be introduced by neglecting the effects of transverse shear stress and rotary inertia. To avoid an overly detailed presentation, the key ideas are illustrated by considering the linear isothermal theory of a straight beam of narrow rectangular cross section, starting from two-dimensional plane stress theory. A complete elaboration of these ideas may be found in

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## **EFFECT OF TRANSVERSE CORE COMPRESSIBILITY IN THE STATIC AND DYNAMIC RESPONSE OF SANDWICH STRUCTURES**

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Sandwich plates and shells consisting of two thin face sheets made from a high density material which are adhesively bonded to a thick core layer, in general consisting of a soft, low density material are important elements in many fields of modern lightweight construction, including aerospace, naval, automotive and other applications. Advantage of this principle of construction is the combination of high bending stiffness and strength with rather low specific weight. On the other hand, sandwich plates and shells have the disadvantage of a rather complex deformation, buckling and postbuckling behavior caused by the thick and weak core layer, which enables the development of additional local buckling and deformation modes.

The present contribution gives an overview of recent developments made in the field of the mechanical modeling of sandwich structures accounting for local instabilities, made by the present author in collaboration with Prof. Liviu Librescu. In order to study the effect of the transverse core compressibility of the core layer on the static and dynamic deformation and buckling response of sandwich panels, a higher order, geometrically nonlinear v. Kármán type sandwich shell theory has been developed. The theory is based on the standard Kirchhoff-Love assumption for the face sheets whereas a higher order expansion is employed for the core displacements. A consistent set of equations of motion and boundary conditions for this model is obtained using Hamilton's variational principle.

The sandwich shell theory has been applied to a variety of static and dynamic problems concerning the buckling and postbuckling response of doubly curved sandwich shells with rectangular projection. For this class of problems, an analytical solution can be obtained based on an assumed form of the transverse displacements in conjunction with an extended Galerkin procedure, resulting in a set of two third order equations for the modal amplitudes of the global buckling and local face wrinkling instability modes. The resulting numerical scheme proves to be both, adequate and numerically efficient.

In a number of parametric studies, the effect of the transverse core compressibility and the related local buckling modes on the global response of sandwich shells is studied. In static buckling, the development of the local instability mode can have severe effects on the overall response by a reduction of the buckling loads and possible further instabilities in the postbuckling range. In dynamic buckling, the development of a face wrinkling instability during the loading process may result in a severe extension of the modal amplitude of the global buckling mode. The resulting vibrations are of the chaotic type with unpredictable amplitudes. In all cases, standard sandwich models assuming an incompressible core would provide inaccurate, non-conservative results.



## ANALYSIS OF THE IMPACT OF A THERMOELASTIC ROD AGAINST A HEATED WALL VIA D'ALEMBERT SOLUTION

**Yuriy A. Rossikhin and Marina V. Shitikova**

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The problem of impact of a thermoelastic rod against a rigid heated barrier was considered repeatedly using different theories of thermoelasticity [1-3]. Thus, Gonsovskii et al. [1] investigated the impact of a thermoelastic rod with a heat-insulated lateral surface against a rigid heated barrier based on the Maxwell-Cattaneo-Vernotte law of heat conduction, and found the solution using the ray method [4]. The similar problem was analyzed by Rossikhin and Shitikova [2] using Green-Naghdy theory of thermoelasticity [5], and the Laplace integral transform with subsequent expansion of the found images in terms of the natural functions of the given boundary-value problem was used as a method of solution. Some particular case was considered in [3]. In none of the papers [1-3] the analytical solution in the closed form for the main functions showing the distribution of the thermoelastic impact characteristics along the rod has been presented.

In the present paper, the problem of the impact of a thermoelastic rod against a heated wall is considered using Green-Naghdy theory at free heat exchange between the bodies. The analytical method based on the solution of the D'Alembert type is used as the method of solution of hyperbolic set of equations describing the behavior of the thermoelastic rod. This solution involves four arbitrary functions which are determined from the initial and boundary conditions and are piecewise constant functions. The procedure developed enables one to analyze the influence of thermoelastic parameters on the values to be found and to investigate numerically the longitudinal coordinate dependence of the desired functions at each fixed instant of the time beginning from the moment of the rod collision with the barrier up to the moment of its rebound both with due account and without account for the stress and temperature fields coupling.

**Acknowledgment** This paper has been partially supported by the Russian Foundation for Basic Research under grant No. 05-08-17936-a.

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## SHAPE AND DEFORMATION MEASUREMENTS OF MATERIALS BY OPTICAL METHODS

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In experimental mechanics, whole-field methods such as photoelasticity, moiré method, moiré interferometry, grating projection method, holography and laser interferometry are used for analyzing shape, displacement, stress, strain and strain rate of structures. Though they provide the qualitative results easily, the quantitative analysis of the obtained photographs is time-consuming and bothersome without a computer. Image processing using a computer is useful to analyze the photographs. The phase analysis of fringe patterns and grating patterns obtained by optical methods is automated and it provides accurate results in a short time.

The authors have been developing some novel methods using optical methods and image processing to measure shape, deformation, stress and strain of structures as follows:

- (1) Phase analysis methods using Fourier, wavelet or Gabor transforms, etc.
- (2) Real-time measurement for two-directional strain distributions using moiré interferometry
- (3) Scanning moiré method using thinning-out of scanning lines and a DMD camera
- (4) Strain rate distribution measurement by a high-speed video camera
- (5) Real-time integrated phase-shifting method
- (6) Shape measurement methods using multi-reference planes, a linear image sensor, or a frequency modulated grating
- (7) Windowed phase-shifting digital holographic interferometry (Windowed PSDHI)
- (8) Whole-space Tabulation Method (WSTM)
- (9) Sampling moiré method

The most accurate method is the Windowed PSDHI for analyzing small displacement and strain. It provides 88 picometer resolution in our experiment. In this presentation, the theories of the optical methods, techniques and know-how of image processing for the phase analysis, and applications to actual objects.

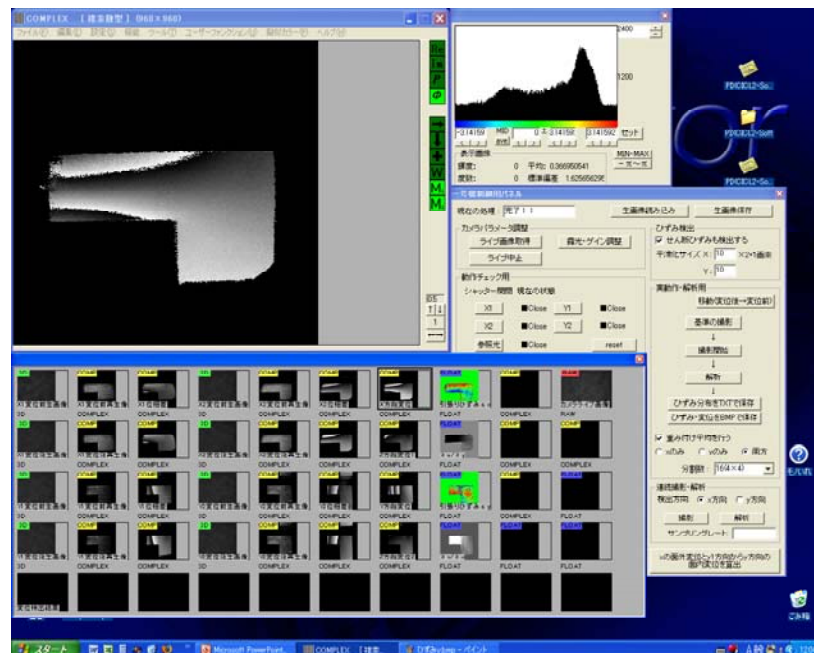


Fig. 1 Analyzer for digital holography



## **DYNAMIC RESPONSE OF A TIMOSHENKO TYPE THIN-WALLED BAR OF MONO-SYMMETRICAL OPEN SECTION IMPACTED BY A SPHERE**

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The problem on the normal impact of an elastic sphere upon an elastic thin walled bar of monosymmetrical open section is considered, in so doing the sphere's centre is at some distance from the vertical axis of cross-section symmetry. The equations of motion of the bar include shear deformation and rotary inertia.

The process of impact is accompanied by the dynamic flexure and torsion of the bar, resulting in the propagation of plane flexural, shear and torsional waves of strong discontinuity along the beam axis. Behind the wave fronts the solution is constructed in terms of one-term and multiple-term ray expansions.

During the impact the sphere moves under the action of the contact force which is determined due to the Hertz's theory, but the contact region (the beam part with the contact spot) moves under the action of the contact force, as well as the bendingtorsional moment and transverse forces, which are subjected to the lateral surfaces of the contact region and are determined in terms of one-term and multiple-term ray expansions.

It is found that in the case of one-term ray expansions, the joint consideration of the equations of sphere and the contact region motion leads to the Abel equation of second kind, wherein the value of the sphere and beam drawing together and the rate of change of this value are used as the independent variable and the function, respectively.

The solution to the Abel equation written in the form of a series allows one to determine all characteristics of the sphere and beam shock interaction. In the case of multiple-term ray expansions, the problem is reduced to the solution of the set of recurrent equations of the ray method.

**Acknowledgements.** The research described in this publication has been made possible in part by the Russian Foundation for Basic Research under the Grant No.05-08-17936-a.



## **Session # 5**

**30 May 2008, Friday (8:00 – 9:45)**

Co-Chairs: **A. J. Levy**, Syracuse University, Syracuse, NY, and **M. Porfiri**, Polytechnic University, Brooklyn, NY

**8:01 – On the Spatial Behavior of Harmonic Vibrations in Linear Thermoelasticity, Chirita S.** (Al. I. Cuza University, ROMANIA)

**8:22 – Vibration Control of Piezo-Composite Beams: A Collaboration with Liviu I. Librescu, Chandiramani N. K.** (IIT-Bombay, INDIA)

**8:43 – Evaluation of Thermal Fracture Parameters for Inclined Cracks in Functionally Graded Materials using  $J_k$ -Integral, Dag S.** (Middle East Technical University, TURKEY) and Yildirim B. (Hacettepe University, TURKEY)

**9:04 – Mechanical Failure of Thin Films Bonded to Graded Substrates, Guler M.A.** (TOBB University of Economics and Technology, TURKEY)

**9:25 – Non-linear Aeroelasticity and Control of Lifting Surfaces: Liviu Librescu Tribute, Marzocca P.** (Clarkson University, USA)





## ON THE SPATIAL BEHAVIOR OF HARMONIC VIBRATIONS IN LINEAR THERMOELASTICITY

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In the present contribution we consider a prismatic cylinder occupied by an anisotropic homogeneous compressible linear thermoelastic material that is subject to zero body force and heat supply and zero displacement-temperature variation on the lateral boundary. The elasticity tensor is strongly elliptic and the motion is induced by a harmonic time-dependent displacement-temperature variation specified pointwise over the basis. We establish some spatial estimates for appropriate cross sectional measures associated with the amplitude of the corresponding harmonic vibration that describe how the amplitude evolves with respect to the axial distance to the excited basis. The results are established without any kind of restriction upon the exciting frequency. We have to outline that the corresponding problem for an isotropic thermoelastic material has been previously treated by S. Chirita (*Spatial decay estimates for solutions describing harmonic vibrations in a thermoelastic cylinder*, Journal of Thermal Stresses 18 (1995), 421-436) under the assumption that the exciting frequency is lower to a certain critical value. The corresponding studies for elastic materials have carried out by J. N. Flavin and R. J. Knops (*Some spatial decay estimates in continuum dynamics*, J. Elasticity 17 (1987), 249-264) and J. N. Flavin, R. J. Knops and L. E. Payne (*Decay estimates for the constrained elastic cylinder of variable cross section*, Quart. Appl. Math. 47 (1989), 325-350)



## **VIBRATION CONTROL OF PIEZO-COMPOSITE BEAMS: A COLLABORATION WITH LIVIU I. LIBRESCU**

**Naresh K. Chandiramani**

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A composite rotating beam with hollow cross section and carrying a tip rotor is analyzed. The beam comprises an orthotropic graphite-epoxy host with surface embedded and spanwise distributed transversely isotropic (PZT-4) collocated sensors-actuator pairs. The tip rotor and rigid hub rotate at constant speeds. Restrained warping, linear and parabolic pretwist variation along span, and taper are considered. Traction-free boundary conditions are satisfied using a parabolic variation of transverse shear strains through the wall thickness. Span- and thickness- wise variation of electric field applied to actuators is considered. This yields coupled electro-mechanical governing equations wherein all six displacement field variables are coupled via the electric field variable - i.e., bending-transverse shear and extension-twist coupling occurs. Spatial discretization is based on the extended Galerkin's method. Optimal control using steady-state LQR with full state feedback is employed. The resulting algebraic Ricatti system is solved via a robust method using stable eigenvectors of the Hamiltonian matrix. Parametric studies involving ply-angle, rotation speeds of beam and rotor, pretwist, taper, rotor mass, and saturation constraint on actuator voltage, are performed. The present higher-order shearable model yields lowest coupled natural frequencies -as compared to unshearable and first-order shear models- thus providing conservative data, useful for passive and active control designs. The present model, with spanwise varying electric field, yields an order-of-magnitude reduction in settling time and control voltage/power required, and also lower controlled response, vis-a-vis the decoupled approach. Gyroscopic forces -due to tip rotor- have a pronounced qualitative effect on the controlled response, in that the attenuation is greater for smaller ply-angles, in contrast with the rotorless system. This underscores the importance of synergizing active control and structural tailoring.



## EVALUATION OF THERMAL FRACTURE PARAMETERS FOR INCLINED CRACKS IN FUNCTIONALLY GRADED MATERIALS USING $J_k$ - INTEGRAL

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<sup>2</sup>Department of Mechanical Engineering, Hacettepe University, Ankara 06800, Turkey

As a line integral defined over a vanishingly small curve at the tip of a crack,  $J_k$  - integral vector has been a useful tool in conducting mixed-mode fracture analysis. In computational studies, especially within the framework of finite element analysis, the generalized definition of the  $J_k$  - integral is generally converted to a domain independent form that consists of area and line integrals which are evaluated over finite domains.

The present study extends the  $J_k$  - integral based analysis approach in order to conduct mixed-mode fracture mechanics analysis of functionally graded materials (FGMs) that are subjected to thermal stresses. The domain independent form of the  $J_k$  - integral is derived by taking into account spatial variations of the thermomechanical properties and the temperature. A procedure is then developed which allows the computation of mixed-mode stress intensity factors (SIFs) and the  $T$  - stress under thermal stress conditions.

Finite element analysis software ANSYS is used in the implementations of the developed numerical methodologies. The domain independence of the modified  $J_k$  - integral is demonstrated by conducting analyses using circular domains of various sizes. Comparisons to the numerical results obtained by the displacement correlation technique (DCT) show that  $J_k$  - integral method leads to computational results of high accuracy.

Some further numerical results are generated by considering inclined cracks subjected to steady-state thermal stresses. Presented numerical results illustrate the influences of material property gradation profiles, crack geometry and thermal loading conditions on the temperature fields and fracture mechanics parameters.



## MECHANICAL FAILURE OF THIN FILMS BONDED TO GRADED SUBSTRATES

**Mehmet A. Guler**

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In this study the basic residual stress problem for a thin film on a graded substrate is considered. In these problems the loading consists of any one or combination of stresses caused by a homogeneous temperature variation or slow thermal cycling and far field mechanical loading, and residual stresses resulting from film processing or welding. The primary interest in this study is in examining stress concentrations or singularities near the film ends for the purpose of addressing the question of crack initiation and propagation in the substrate or along the interface. The underlying contact mechanics problem is formulated by assuming that the film is a “membrane” and the substrate a graded elastic continuum, and is solved analytically by reducing it to an integral equation. The calculated results are the interfacial shear stress between the film and the graded substrate, mode II stress intensity factor at the end of the film and the axial normal stress in the film.



## NON-LINEAR AEROELASTICITY AND CONTROL OF LIFTING SURFACES: LIVIU LIBRESCU TRIBUTE

**Pier Marzocca**

MAE Dept, Clarkson University, Potsdam, NY

Active aeroelastic control is a recently emerging technology aimed at providing solutions to a large class of problems involving the aeronautical/aerospace flight vehicle structures that are prone to instability and catastrophic failures. The flight vehicles should feature increasing structural flexibilities, should be highly maneuverable, and at the same time, should be able to operate safely in severe environmental conditions.

As a necessary requirement, the issue of the non-occurrence of any aeroelastic instability within its flight envelope, and that of being able to fly in the vicinity of the flutter instability boundary, are conditions of most importance. The successful fulfillment of all these demands requires the implementation of adequate control capabilities. In this context, the linear and nonlinear aeroelastic controls are applied: I. to alleviate and even suppress the vibrations appearing in the subcritical flight speed range; II. enlarge the flight envelope by increasing the flutter speed; and III. enhance the post-flutter behavior by converting the unstable limit cycle oscillation (LCO) to a stable one.

This presentation will review Professor Librescu and the author recent contributions to the field of unsteady aerodynamics, aeroelasticity and control of lifting surfaces. Various control strategies applied to linear and nonlinear aeroelastic behaviors are discussed. Analytical tools, such as Volterra series and indicial functions, have been used to reduce the often complex computational aerodynamics and also to identify and provide insight on the contribution of the nonlinearities in the dynamics of a structural system, whereas Lyapunov and center manifold theory have been used for the analysis of the Hopf-Bifurcation.

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## Session # 6

**30 May 2008, Friday (10:15 – 12:00)**

Co-Chairs: **J. B. Kosmatka**, University of California San Diego, San Diego, CA, and **M.A. Guler**, TOBB University of Economics and Technology, Ankara, Turkey

**10:16 – Illustrating the Advantages of a Bayesian Over a Least Squares Approach to Material Properties Identification**, Gogu C., **Haftka R.T.** (University of Florida, USA), Le Riche R., Molimard J. and Vautrin A (Ecole des Mines de Saint Etienne, FRANCE)

**10:37 – High-Order Spectral Analysis to Investigate Non-linear M-DOF Structural Systems**, Nichols J. (NRL, USA), Milanese A. and **Marzocca P.** (Clarkson University, USA)

**10:58 – Mechanical Characterizations of Protein Crystal Structure**, **Park H.**, Yoon G., Eom K. and Na S.S. (Korea University, SOUTH KOREA)

**11:19 – Estimating the Covariance of Composite Properties with Measurement Uncertainty and Material Correlation Models**, Smarslok B.P., Haftka R.T. and Ifju P. (University of Florida, USA)

**11:40 – Thermal Effects of Ferro/Magnetic Materials Under Cyclic-Electric Loading**, **Yu S.** and Zhang L. (Tsinghua University, CHINA)





## ILLUSTRATING THE ADVANTAGES OF A BAYESIAN OVER A LEAST SQUARES APPROACH TO MATERIAL PROPERTIES IDENTIFICATION

Gogu C.<sup>1,2</sup>, Haftka R.T.<sup>1</sup>, Le Riche R.<sup>2</sup>, Molimard J.<sup>2</sup>, and Vautrin A.<sup>2</sup>

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Identifying parameters of a model using experimental data has been extensively studied in various areas, including for determining mechanical material properties from strain measurements or modal vibration data. In order to find the parameters that make the model agree best with the experiments, the most widely used method is based on minimizing the least-squares error between the experimental data and the model predictions.

An alternative way to identify the material properties is through statistical frameworks, based on maximum likelihood or on Bayes' rule. The Bayesian framework is more general since it can include prior knowledge. Isenberg proposed the application of the Bayesian framework for parameter estimation in 1979 and several articles have been published since on the application of this approach to frequency or modal identification in particular, i.e. identifying material properties from vibration test data.

Here we compare the least-squares and the Bayesian approach to material properties identification, seeking situations where the properties identified by the two approaches are significantly different. We chose a simple, didactic example of a three bar truss so that the results of the comparison are not clouded by unnecessary complexity or computational issues.

For the three bar truss example we seek to identify the Young modulus of the bars from strain measurements on these bars. Due to uncertainty in the loads applied on the truss, which propagate to variability in the strains, the different strain measurements provide conflicting information. The least-squares approach and the Bayesian approach combine this conflicting information differently to come up with the identified Young modulus.

We found that the least-squares method can be negatively affected by differences in magnitudes of the experimental data, by differences in uncertainty and by correlation among the experimental data. The least-squares method does indeed implicitly weight strains depending on their sensitivity to Young's modulus. This negatively impacts the results found by the least-squares approach. Different uncertainty in the strains in each bar also negatively affects the least-squares approach, which does not differentiate between a strain with low uncertainty and one with high. Last, the least-squares approach does not handle correlation between the strain measurements.

On the other hand the Bayesian correctly handles these three situations, namely different strain magnitude, uncertainty and correlation. We found that in each situation the Bayesian approach systematically outperforms the least-squares approach. In the case when all three effects act combined, we found that the Young modulus identified by the Bayesian approach is on average almost 10 times closer than least-squares to the true value of the Young modulus.



## HIGH-ORDER SPECTRAL ANALYSIS TO INVESTIGATE NON-LINEAR M-DOF STRUCTURAL SYSTEMS

**Jonathan M. Nichols<sup>1</sup>, Attilio Milanese<sup>2</sup>, and Pier Marzocca<sup>2</sup>**

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<sup>2</sup>Mechanical and Aeronautical Engineering Dept, Clarkson University, Potsdam, NY

Higher order spectral analysis techniques are often used to identify nonlinear interactions in modes of complex dynamical systems. The auto-bispectral density, commonly known as the bispectrum, is one example of a higher-order spectrum and may be used in the analysis of stationary structural response data to detect the presence of certain types of structural nonlinearities. In particular, the bispectrum and the trispectrum have proven to be useful tools in testing for the presence of quadratic and cubic nonlinearities based on a system's stationary response. In this presentation a class of M-DOF mechanical system represented by a second-order nonlinear ordinary differential equation subject to Gaussian white noise forcing is considered.

Analytical expressions for the second- and third order auto- and cross-spectra are determined using a Volterra functional approach and the presence and extent of nonlinear interactions between frequency components are identified. The Volterra series model of the system response yields expressions for both "homogeneous spectra", where the output of only one degree-of-freedom is used, and "mixed spectra", where the bispectral density contains multiple response time series. Numerical simulations accompany the analytical solutions to show how modes may interact nonlinearly producing intermodulation components at the sum and/or difference frequency of the fundamental modes of oscillation. Further we show how the proposed technique can be used to identify the source of non-linearity due to interactions at specific frequencies. Such identification tools can be used as a benchmark for validation of nonlinear analysis methods associated to structural health monitoring techniques and to reduce the burden associated with these methods. Results show that the ability to detect and the localize nonlinearity is heavily dependent on which particular bi- and tri-spectral density is utilized.

The properties of nonlinearity detectors based on estimates of the magnitude of the auto-bispectral density at the bispectral frequency most sensitive to the nonlinearity are then explored. Estimates of the auto-bispectral density are obtained using the direct method based on the discrete Fourier transform. The bias associated with this estimator combined with the estimator variance is used to derive the distributions for the magnitude bispectral density peak height. These distributions allowed for both Type-I and Type-II error to be solved for analytically for the auto-bispectral density-based detector. Detector performance is quantified using a Receiver Operating Characteristic (ROC) curve illustrating the trade-off between false positives (Type-I error) and power of detection (1.0-Type-II error) and are used to display these errors in detecting both damping and stiffness nonlinearities. Theoretically derived ROC curves are compared to those obtained via numerical simulation and show excellent agreement.

Results are presented for different levels of nonlinearity in both the stiffness and damping terms for a spring-mass system. These results focus only on the uncertainty due to errors in the estimation. In this sense the ROC curves presented show the fundamental limits of autobispectral density-based detector performance for single degree-of-freedom systems with quadratic nonlinearities using the direct method of estimation. Possible consequences are discussed with regard to the detection of damage-induced nonlinearities in structures.

### Acknowledgments

Pier Marzocca wishes to thank ASEE/ONR Summer Fellowship program for the financial support provided during the summer of '06 and '07.



## MECHANICAL CHARACTERIZATIONS OF PROTEIN CRYSTAL STRUCTURE

**Hyeongjin Park<sup>1</sup>, Gwonchan Yoon<sup>1</sup>, Kilho Eom<sup>2</sup> and Sungsoo Na<sup>1</sup>**

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Mechanical characterization of proteins have recently enabled the understanding of their mechanical and/or biological functions. Moreover, the studies on mechanical functions of proteins have recently allowed for gaining insight into how to design the novel materials which can perform the excellent mechanical functions based on biomimetics. For instance, proteins have been known to perform the excellent mechanical functions and exhibit the remarkable mechanical properties such as high fracture toughness in spider silk protein [1]. This indicates that the mechanical characterization of protein molecules and/or crystals is very essential to understand such remarkable mechanical function of protein molecules.

In this study, for gaining insight into mechanical behavior of protein crystals, we developed the micromechanical model by using the empirical potential field prescribed to alpha carbon atoms of a protein crystal in an unit cell[2]. We considered  $\alpha$ -helix and  $\beta$ -sheet as the basic structure of protein crystals under the tensile loading for their mechanical behavior. In addition, to validate our coarse-grained model, we considered protein models such as tubulin,  $\alpha$ -lactalbumin, etc to be compared with full atomic model and/or experimental data.

**Table 1. Elastic property of protein crystals**

Protein (PDB* ID)	Space Group	# of residue in unit cell	Unit cell** (Å <sup>3</sup> )	Normalized contact number	Elastic modulus (GPa)
$\alpha$ -helix (1akg)	P2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub>	64	14.6×26.1×29.2	0.117	0.277
$\beta$ -sheet (2ona)	P <sub>1</sub>	24	25.8×9.7×15.8	0.294	0.433
Titin proximal Ig domain (1g1c)	P2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub>	640	38.3×78.6×79.6	0.0129	0.187
Titin distal Ig domain (1waa)	P2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub>	2208	62.2×75.9×134.2	0.00406	0.254
$\alpha$ -lactalbumin (1hfs)	P2 <sub>1</sub>	982	58.6×60.1×77.1	0.00875	0.186
Transthyretin (2g5u)	P2 <sub>1</sub> 2 <sub>1</sub> 2	908	43.2×85.8×64.7	0.0104	0.242
Tubulin (1tub)	P2 <sub>1</sub>	1734	80×92×90	0.00565	0.138

\*. Protein Data Bank

\*\*, a×b×c

## ACKNOWLEDGEMENT

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## **ESTIMATING THE COVARIANCE OF COMPOSITE PROPERTIES WITH MEASUREMENT UNCERTAINTY AND MATERIAL CORRELATION MODELS**

**Benjamin P. Smarslok, Raphael T. Haftka, and Peter Ifju**

University of Florida, Gainesville, FL 32611

In probabilistic design of composite structures, elastic properties, such as moduli, are often treated as independent random variables, which implies that significant correlations amongst properties do not exist. However, high correlations are expected, because variability in elastic properties are traceable to common physical effects such as variability in fiber volume fraction. In addition to material variability, measurement error is another source of uncertainty in estimating elastic properties that is expected to exhibit correlations because different properties are often measured in a single experiment or in the same laboratory. Correlations in material properties can have large effect on the probability of failure, so treating the properties as independent can be mostly attributed to lack of data on correlations.

The proposed paper takes a first step in facilitating the generation of correlated data, by developing a general correlation model that accommodates two types of uncertainty in composite properties: material variability and measurement uncertainty. Linear relationships of the properties with respect to fiber volume fraction were used to construct a correlation model for material variability. The measurement uncertainty was estimated by using coefficients of variation from experimental data. The material variability and measurement uncertainty were combined to generate a covariance matrix of the composite properties.

The covariance is presented in general terms to handle the input of normal parameters associated with any estimate of measurement uncertainty. Simulations were also conducted for material properties with uniform distributions and compared to the normal case. An example case was considered to determine the significance of the relationship between properties and the sensitivity to material variability and measurement uncertainty. Reducing the uncertainty in either component represented the effect of using advanced experimental techniques (measurement error) or improving the manufacturing process (material variability).

The uncertainty in elastic properties was propagated to strain under mechanical and thermal loading using Classical Lamination Theory, for comparison of coefficients of variation. The sensitivity from uncertainty in each material property was compared by propagating the uncertainty to mechanical and thermal strains. Failure probability was calculated based on a maximum strain criterion. It was found that correlation amongst composite properties can have large effects on the probability of failure from both thermal and mechanical loading. Additionally, focusing experimental efforts on only the most sensitive properties can greatly reduce the uncertainty in the strain response.



## **THERMAL EFFECTS OF FERRO/MAGNETIC MATERIALS UNDER CYCLIC- ELECTRIC LOADING**

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Ferroelectric and ferromagnetic materials are important smart materials and have widespread engineering application. The temperature in the materials may increase because of energy dissipation under loading, which is so-called thermal effect. Thermal effect on the mechanical behavior in ferroelectric and ferromagnetic materials is investigated by theoretical modeling and numerical computation. In the studies of thermal effect in ferroelectrics, the influence of stress induced by domain switching on further domain reversal is firstly investigated; and then based on the electrical saturation model, changes of stress and electric intensity factors brought by thermal effect are obtained, meanwhile the accumulative influence of temperature increment on domain inverting and fracture behavior for ferroelectrics under cycle electric field is numerically studied. For ferromagnetic materials, temperature fields in various instances are numerically achieved and the heat effect on the mechanical behavior for ferromagnetic materials is investigated, after the heat source is solved according to the conception of work conjugate in thermodynamics.

Based on the electrical saturation model, the influence of thermal effect on the domain switching is studied, and the results indicate that the thermal effect can promote domain switching. The results show that the thermal effect can restrain crack extension. With the times of loading increasing, the restraining function becomes more obvious. The effect of restraining the crack propagation is related to the wave shape and the frequency of electric loading. Similar for the approach of ferroelectric materials, based on the model of magnetic saturation, the temperature fields under different conditions are calculated by finite difference method. It is found that in the ferromagnetic materials with a slender elliptic crack, the magnitude of temperature increment strongly depends upon the geometrical shape of crack, the frequency and wave shape of the magnetic loading. In addition, we investigate the influence of thermal effect on the mechanical behavior of ferromagnetic materials. The solutions show that the thermal effect can enhance the fracture toughness of ferromagnetic materials, and that the effect depends also on the geometrical configuration of crack, the frequency and wave shape of the magnetic loading.



## **Session # 7**

**30 May 2008, Friday (13:30 – 15:15)**

Co-Chairs: **J. C. Bruch, Jr.**, University of California Santa Barbara, Santa Barbara, CA, and **S. Dag**, Middle East Technical University, Ankara, Turkey

**13:31 – Toughening of Silica Aerogels – Molecular Dynamics Simulations, Murillo J.S.R.** (West Virginia University), **Bachlechner M.E.** (Fairmont State University, USA), **Barbero E.J.** and **Cairns D.** (West Virginia University, USA)

**13:52 – Three-Dimensional Transient Analysis of Microelectromechanical Systems, Das K.** and **Batra R.C.** (Virginia Tech, USA)

**14:13 – Biomechanics of Epidermal Wound Closure in Embryos, Wan F.Y.M.** and **Sadovsky A.** (University of California-Irvine, USA)

**14:34 – A Mixture Theory Model of Ionic Polymer Metal Composites, Del Bufalo G.** (Polytechnic University, USA), **Placidi L.** (La Sapienza, ITALY) and **Porfiri M.** (Polytechnic University, USA)

**14:55 – Locally-Exact Homogenization Theory for Periodic Materials: Further Developments, Drago A.** and **Pindera M.-J.** (University of Virginia, USA)





## TOUGHENING OF SILICA AEROGELS – MOLECULAR DYNAMICS SIMULATIONS

**John Sandro Rivas Murillo<sup>1</sup>, Martina E Bachlechner<sup>2</sup>, Ever J. Barbero<sup>3</sup>, and Darran Cairns<sup>4</sup>**

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<sup>4</sup> Assistant Professor, Mechanical and Aerospace Engineering, West Virginia University, Morgantown, WV.

Silica-based aerogels have the highest specific thermal and acoustic insulation properties of any material and in addition are optically translucent. The combination of excellent optical and insulating properties makes them ideal for ultra-high performance windows. However, their applicability has been limited due to their fragility. Aerogels are very complex materials produced by the sol-gel process. They have a complex morphology resulting in a very low density material composed of a complex skeletal structure filled with nanoscale pores. The skeleton is made of silica but the energy absorption and mechanical properties of the aerogel do not necessarily scale up from the properties of silica following classical mechanisms. This presentation focuses on molecular dynamic simulation of silica aimed at shedding light on the stiffness, strength, and toughness of various silica compositions, crystal/amorphous structures, and ultimately of the silica-based aerogel. Various aspects of the simulation process will be discussed, such as the methods used for creating amorphous silica, creating free surfaces, applying strain, maintaining an isothermal condition, and so on. Results will be presented for amorphous, crystalline  $\alpha$ -cristobalite, multi-crystalline  $\alpha+\beta$ -cristobalite, and so on. This is preliminary work leading towards the first author's dissertation. Further work will be briefly summarized.

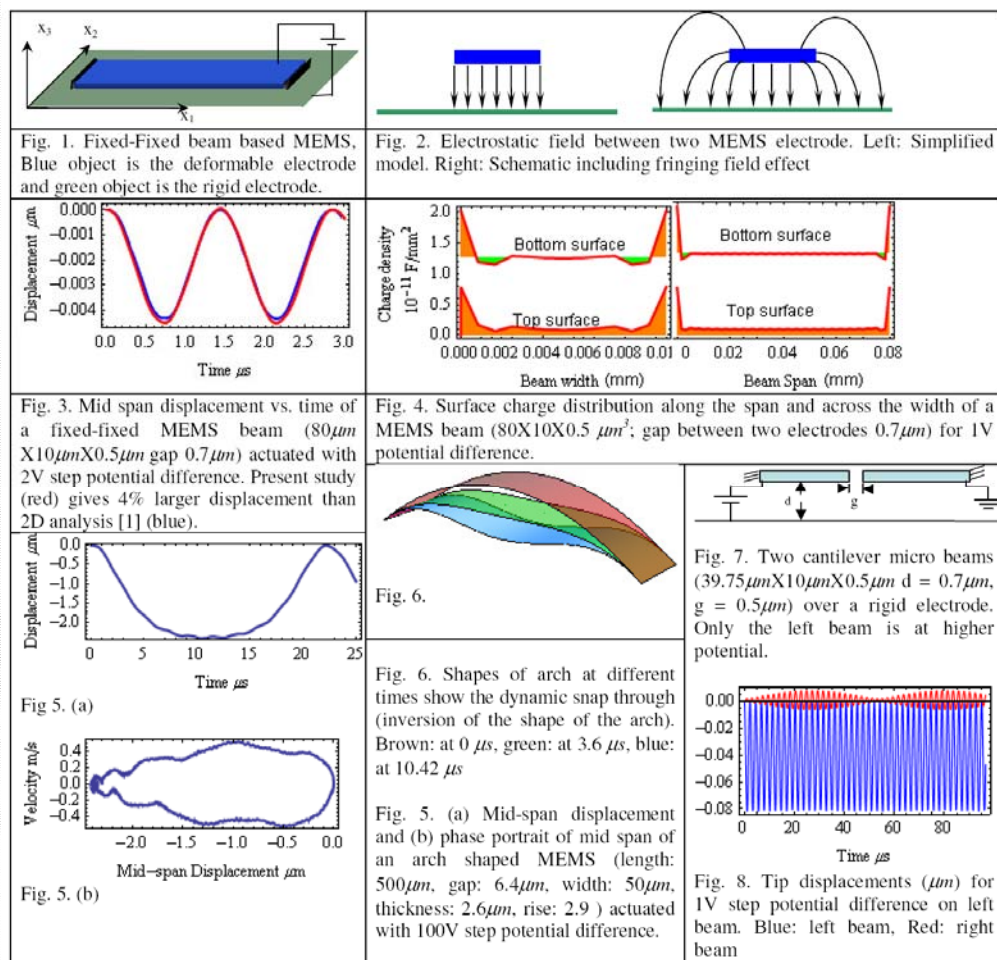


# THREE-DIMENSIONAL TRANSIENT ANALYSIS OF MICROELECTROMECHANICAL SYSTEMS

K. Das and R. C. Batra

Department of Engineering Science and Mechanics, Virginia Tech

A typical micro-electro-mechanical system (MEMS) consists of a deformable electrode held over a rigid one as shown in Fig. 1. The Coulomb force between the two electrodes actuates the deformable one and at a certain value of the voltage, the deformable electrode suddenly undergoes severe deformations so as to close the gap between the two electrodes. This voltage and the corresponding deflection are called pull-in parameters. The solution of the problem requires solving a set of coupled nonlinear partial differential equations of electro-elasto-dynamics. We have solved numerically both two and three-dimensional problems by coupling the finite element and the boundary element methods; the former for the structural problem and the latter for the electrical fields. For the three MEMS configurations (cf. Figs. 1, 6 and 7) studied, we consider fringing fields that account for the deformed shape of the electrode, and also examine effects of ramping up the applied voltage on the pull-in parameters. For the arch shaped MEMS of Fig. 6, we have also investigated the snap-through instability. The final problem studied is the transient response of two micro-cantilevers with their free ends placed to each other in an electrodynamic environment (Figs. 7 & 8). This has applications in Bio-MEMS.



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## BIOMECHANICS OF EPIDERMAL WOUND CLOSURE IN EMBRYOS

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Epidermal wounds in early mammalian embryos are known to heal without inflammation or scarring, serving as an excellent biological model of successful wound repair. A crucial role in the closure of such wounds is ascribed to an experimentally observed process known as the purse string phenomenon. It consists of the actin filaments in the epidermis near the wound realigning so that a thick cable is formed around the wound and contracts as the wound closes. Experiments have shown the purse string phenomenon necessary for wound closure. To investigate quantitatively whether it is also sufficient, we propose a mathematical model describing the closure of such wounds as a biomechanical process, regarding the epidermis surrounding the wound as a 2-D deformable living body with a certain constitutive behavior. The model has two main conceptual components. The first component is a mechanism for the detection and assessment of the wound, based on a hypothetical cell-cell signaling system with certain geometric and temporal properties. The second component is a tensorial formulation of the purse string phenomenon. Our numerical simulations of this 2-dimensional model suggest that, in the absence of such biological phenomena as cell proliferation, migration, and differentiation, the purse string phenomenon will close a wound in an epidermis that is a linearly viscous fluid or a nonlinearly viscoelastic solid.



## A MIXTURE THEORY MODEL OF IONIC POLYMER METAL COMPOSITES

**Giovanni Del Bufalo<sup>1</sup>, Luca Placidi<sup>2</sup>, and Maurizio Porfiri<sup>1</sup>**

<sup>1</sup>Department of Mechanical and Aerospace Engineering, Polytechnic University, Brooklyn, NY 11201

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An Ionic Polymer Metal Composite (IPMC) is a porous charged polymer saturated with an electrolytic solvent and plated by two metallic electrodes. A voltage difference across the electrodes generates structural deformations; and, vice-versa, a mechanical deformation yields a voltage difference across the electrodes. The electrolytic solvent comprises a mobile ionic species and an uncharged solvent. Interactions between mobile the ions and the solvent and between the solvent and the backbone polymer are responsible for sensing and actuation.

In this talk, we present a mixture theory framework for mechanical modeling of IPMCs and of species interactions occurring therein. The proposed framework accounts for the simultaneous effects of osmotic pressure, hydraulic pressure, and electrostatic forces on IPMCs behavior, and it is applicable to a large variety of IPMCs' geometries and microstructures. For small deformations of the IPMCs and limited applied voltage differences, the model reduces to three coupled linear partial differential equations. The linearized model allows for a quantitative understanding of the different electromechanical phenomena that take place in an IPMC, including: i) the migration of mobile ions due the electric field generated by the voltage difference across the electrodes; ii) the displacement of the solvent towards the cathodic region due to the hydrophilic behavior of mobile ions; and iii) the expansion of the backbone polymer in the vicinity of the cathodic region due to the hydrophobic behavior of the polymer. In addition, the linearized model describes the presence of boundary layers of mobile ions and solvent concentrations in the vicinity of the electrodes.

We particularize the general three dimensional model to a slender IPMC, and we derive a one dimensional distributed model using the Euler-Bernoulli beam theory and a parallel-plate approximation. We validate the developed static model on a cantilever beam-like IPMC by comparing theoretical predictions with experimental results. Experiments are conducted on IPMCs comprising Nafion117 as the backbone polymer matrix and platinum metal as the electrodes' material.  $\text{Na}^+$  is selected as mobile ionic species. Experiments are conducted in deionized water and IPMCs' deformations were measured using an in-house developed vision based measurement system. Experimental data seem to confirm a fairly linear relation between IPMCs' deformation and applied voltage in a wide operation range.



## LOCALLY-EXACT HOMOGENIZATION THEORY FOR PERIODIC MATERIALS: FURTHER DEVELOPMENTS

**Anthony S. Drago and Marek-Jerzy Pindera**

University of Virginia, Charlottesville, Virginia, USA

Micromechanical analysis of periodic heterogeneous media is based on the concept of a repeating unit cell (RUC). The RUC is the smallest element of a periodic microstructure which serves as the basic building block for the material, and thus the response of the entire array under macroscopically uniform loading is identical to that of an arbitrary RUC under the same loading. The loading is specified by periodic boundary conditions imposed on the surface displacements and tractions. This contrasts with the micromechanical analysis of statistically homogeneous materials based on the concept of a representative volume element (RVE) which responds in a manner identical to that of the entire assemblage under homogeneous tractions or displacement boundary conditions, Drago and Pindera [1]. Unfortunately, there are no geometric models that satisfy the homogeneous boundary condition equivalence under all loading conditions. This intrinsic difficulty has contributed to the development of analysis methods for periodic materials, with the homogenization technique emerging as a dominant tool. This technique employs a multiscale displacement representation in the solution of the RUC problem which leads to the determination of homogenized moduli and internal strain and stress fields. The solution of the RUC boundary-value problem, however, is typically generated using the finite-element method.

An attractive alternative to the finite-element solutions of the unit cell problem is the recently developed elasticity-based locally-exact homogenization theory for periodic materials, Drago and Pindera [2]. In this approach, the interior inclusion problem is solved exactly using Fourier series representation of the local displacement field. The exterior unit cell periodic boundary value problem is tackled using a new variational principle for this class of non-separable elasticity problems, which leads to exceptionally fast and well-behaved convergence of the Fourier series coefficients. Closed-form expressions for the homogenized moduli of unidirectionally-reinforced heterogeneous materials were obtained in terms of Hill's strain concentration matrices valid under arbitrary combined loading, which yielded the homogenized Hooke's law. Homogenized engineering moduli and local displacement and stress fields of unit cells with off-set fibers, which required the use of periodic boundary conditions, were compared with corresponding finite-element results demonstrating excellent correlation.

Herein, convergence characteristics of this locally-exact homogenization theory for periodic materials are examined vis-a-vis the manner of implementing the periodicity conditions on the unit cell boundaries. Specifically, we compare the solution's convergence behavior based on three additional ways of implementing the periodic boundary conditions which include collocation, least-squares and Jirousek's constrained potential energy-based method, with that based on our derivative balanced variational principle to demonstrate its advantages.

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## **Session # 8**

**30 May 2008, Friday (15:45 – 17:55)**

Co-Chairs: **M.V. Shitikova**, Voronezh State University of Architecture and Civil Engineering, Voronezh, Russia, and **S. Chirita**, Al. I. Cuza University of Iasi, Iasi, Romania

**15:46 – Mechanical Modeling of Hollow-Particle Filled Composites**, Tagliavia G., Porfiri M. and Gupta N. (Polytechnic University, USA)

**16:07 – Antiplane Shear Problems for the Homogenized Fiber Composite with Nonlinear Interface**, Levy A.J. (Syracuse University, USA)

**16:28 – Parametric FVDAM vs FE Analysis of Multilayers with Wavy Architectures**, Khatam H. (University of Virginia, USA), Cavalcante M., Marques S. (University of Alagoas, BRAZIL) and Pindera M.-J. (University of Virginia, USA)

**16:49 – A Mixture Theory for Microstretch Thermo-Elastic Solids**, Gales C.B. (Al. I. Cuza University of Iasi, ROMANIA)

**17:10 – Generalized Solutions in Elasticity of Initially Stressed Materials with Voids**, Marin M. (University of Brasov, ROMANIA)

**17:35 – Thermal Distributions Around an Axisymmetric Insulated Barrier in a Non-homogeneous Semi-Infinite Medium**, Sahin A. (Fatih University, TURKEY)





## MECHANICAL MODELING OF HOLLOW-PARTICLE FILLED COMPOSITES

**Gabriele Tagliavia, Maurizio Porfiri, and Nikhil Gupta**

Department of Mechanical and Aerospace Engineering, Polytechnic University, Brooklyn, NY 11201

Lightweight closed pore foams are synthesized by dispersing hollow microspheres, called microballoons, in a matrix material. Such composites are found to be highly damage tolerant and energy absorbent under a variety of loading conditions. Hollow-particle filled composites, called syntactic foams, are used as core materials in sandwich structures for aerospace and marine structural applications. Elastic properties, strength, and damping capacity play an important role in defining the performance of syntactic foams. These properties can be tailored by selecting appropriate matrix material and microballoon material, wall thickness, and volume fraction. This talk focuses on modeling and experimentally characterizing the static and dynamic Young's modulus, the loss tangent, and the static strength of hollow-particle filled composites.

A differential scheme is used to derive an accurate and tractable expression for the static Young's modulus of syntactic foams containing high volume fraction of microballoons. The dynamic Young's modulus and the loss tangent are determined by generalizing the elastic solution to the dynamic case through the elastic-viscoelastic correspondence principle. The static strength of such composites is determined by solving a tensile problem on a unit cell comprising a single microballoon surrounded by the matrix material. Vinyl ester is selected as the matrix material in the present study due to its recognized superior properties and lower cost compared to other polymeric materials used in naval applications. Glass microballoons are selected as material reinforcement, due to their high mechanical stiffness. Sixteen compositions of syntactic foams are synthesized by using microballoons of four different wall thicknesses in four volume fractions. Particle wall thickness spans from 3 to 7% of the particle radius. Particle volume fractions are varied from a moderate value of 30% to 60% that is nearly the packing limit. Static elastic properties and static Young's modulus are identified through three-point bending tests on slender specimens. Dynamic Young's modulus and loss tangent are identified through vibration tests conducted in a wide frequency range.

Theoretical analyses are in very good agreement with experimental findings in predicting the following trends: i) increase in the volume fraction of thick-walled particles generally results into an increase of the Young's modulus of the composite; ii) increase in the volume fraction of thin-walled particles leads to a decrease of the Young's modulus; and iii) static strength and loss tangent decrease as the particle volume fraction increases at a given particle wall thickness, and are not drastically affected by the wall thickness. The success of the model in predicting static and dynamic properties of composite containing a wide range of particle volume fraction may enhance the current predictive capabilities for porous composites and for composites containing multilayered coated particles.



## **ANTIPLANE SHEAR PROBLEMS FOR THE HOMOGENIZED FIBER COMPOSITE WITH NONLINEAR INTERFACE**

**Alan J. Levy**

Department of Mechanical and Aerospace Engineering  
Syracuse University, Syracuse, New York 13244-1240

This presentation examines recent work on the mechanics of a homogenized nonlinear fiber composite medium composed of linear elastic constituents separated by nonlinear decohesive interfaces. Both torsion of a cylindrical rod and the screw dislocation singularity are considered because (i) antiplane shear (in the fiber direction) is the only active deformation mode in these problems allowing study of nonuniform fields in a relatively simple setting and (ii) there is an intimate relationship between the torsion solution and the singular solution of the dislocation problem. Our primary focus however is on the screw dislocation singularity where the goal is to understand how defects precipitate localized debonding and decohesive failure at the fiber matrix interfaces. The analysis employs a constitutive relation [1], derived from effective property analysis, which utilizes Needleman-type nonlinear interface traction-slip relations [2]. Previous work by the author and coworkers on the torsion of circular shafts [3] and the bending and buckling of symmetrical beams and columns [4] has shown that this constitutive relation can precipitate singular surfaces (damage fronts) in the response of homogenized composite media subject to spatially varying stress and/or deformation fields. This presentation examines how these sharp boundaries, separating regions of maximal and minimal fiber slip, behave in the presence of the screw dislocation singularity.

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## PARAMETRIC FVDAM VS FE ANALYSIS OF MULTILAYERS WITH WAVY ARCHITECTURES

H. Khatam<sup>1</sup>, M. Cavalcante<sup>2</sup>, S. Marques<sup>2</sup> and M-J Pindera<sup>1</sup>

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<sup>2</sup> Federal University of Alagoas, Maceio, Alagoas, BRAZIL

Materials and structural components with periodic wavy architectures span several scales. At the structural level, periodically corrugated cross sections are used to stiffen light-weight panels. In laminated composite plates with thick cross sections, layer waviness often develops during the manufacturing process, producing degradation in compressive strength, while unavoidable fabrication-induced fiber waviness occurs in thin composite laminates. At the material level, periodic microstructures with wavy architectures occur in nature to serve a variety of functions, such as opening and closing of heart valve leaflets by chorda tendinea with different collagen fibril crimp patterns which exhibit stiffening at different stretches. Multilayers with wavy lamellar architectures also have been identified in the rapidly developing nanotechnology areas.

Micromechanical analysis of materials with periodic microstructures, including periodic multilayers with wavy architectures, is typically based on the homogenization theory. This technique employs a multiscale displacement representation in the solution of the unit cell problem which leads to the determination of the effective or homogenized elastic moduli and internal strain and stress fields. The solution of the unit cell boundary-value problem, however, is typically generated using the finite-element method. An attractive alternative to the finite-element approach is the finite-volume theory developed by Bansal and Pindera [1]. The recent incorporation of parametric mapping capability into this theory by Gattu et al. [2], based on the work of Cavalcante et al. [3] in the context of the structural version of the theory, has enabled efficient modeling of complicated microstructures using arbitrarily shaped quadrilateral subvolumes in place of the rectangular subvolumes employed in the original version. Modeling of curved boundaries using rectangular discretization introduces artificial stress concentrations at the corners of subvolumes adjacent to material interfaces. This problem has now been overcome with the parametric mapping. Both the material and structural versions have produced a paradigm shift in the continuing development of this approach for modeling materials and structural components with heterogeneous microstructures.

Herein, we investigate the effect of ply waviness on the homogenized moduli and internal stress fields of periodic multilayers composed of alternating soft and stiff laminae using both the parametric finite-volume theory and the finite-element method to demonstrate the efficacy of the former. The results are compared with those generated using a reference periodic multilayer comprised of flat laminae, for which exact homogenized stiffness matrix elements are available, to demonstrate the effect of ply waviness on the loss of transverse isotropy as a function of the hard layer volume fraction and amplitude-to-wavelength ratio.

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## **GENERALIZED SOLUTIONS IN ELASTICITY OF INITIALLY A MIXTURE THEORY FOR MICROSTRETCH THERMOELASTIC SOLIDS**

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A nonlinear theory is introduced for a heat-conducting viscoelastic composite which is modelled as a mixture consisting of a microstretch Kelvin-Voigt material and a microstretch elastic solid. The strain measures, the basic laws and the constitutive equations are examined and presented in lagrangian description. The initial boundary value problem is formulated. Finally, the theory is linearized and the constitutive equations are given for both anisotropic and isotropic bodies.



## STRESSED MATERIALS WITH VOIDS

**Marin Marin**

Department of Mathematics, University of Brasov, Romania

In our study, the general results from the theory of elliptic equations are applied in order to obtain the existence and uniqueness of the generalized solutions for the boundary value problems in Elasticity of initially stressed bodies with voids.

The theories of bodies with voids do not represent a material length scale, but are quite sufficient for a large number of the solid mechanics applications. Our present paper is dedicated to the behavior of the porous solids in which the matrix material is elastic and the interstices are voids of material. The intended applications of this theory are to the geological materials, like rocks and soils and to the manufactured porous materials.

First, we write down the basic equations and conditions of the mixed boundary value problem within context of linear theory of initially stressed bodies with voids, as in the papers [3], [4]. Next, we use some general results from paper [2] and book [6], in order to obtain the existence and uniqueness of a weak solution of the formulated problem. For convenience, the notations chosen are almost identical to those of [3], [4].

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## THERMAL DISTRIBUTIONS AROUND AN AXISYMMETRIC INSULATED BARRIER IN A NONHOMOGENEOUS SEMI-INFINITE MEDIUM

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The main interest of this study is to determine the thermal distribution around an insulated crack due to constant heat flux in a nonhomogeneous (Functionally Graded) semi-infinite medium. It is assumed that the uniform heat flux is applied over the stress free boundary. Using superposition method, the conduction problem is solved in two cases: Linear (one-dimensional) heat conduction problem under constant heat flux without a crack and a nonlinear (two-dimensional) heat conduction problem with an insulated crack subject to constant heat flux, which is acted in the opposite direction. It is started with the one dimensional problem whose solution can be obtained by a standard process and it has close form solution,  $T_1(z)$ . The second problem (mixed boundary value problem) is two-dimensional heat conduction problem,  $T_2(r, z)$  which may be expressed as a singular integral equation in terms of unknown function, so-called density function. Starting with asymptotical analysis of kernels to separate singularities from the integrand the problem is turned into a system of linear equations to be solved numerically and the thermal distribution around an insulated crack is expressed in terms of inhomogeneity parameter and the length parameter of FGMs.



## MATHEMATICAL MODELING AND ANALYSIS OF MAGNETO THERMO-ELASTIC PLATE

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Nonlinear equations of thermo-elastic plate in an electromagnetic field are developed with consideration of a material nonlinearity. Using the Maxwell's equations for electromagnetic field, the modified Fourier law of heat conduction and elastokinetic field equations, the three-dimensional coupled problem is reduced to a two-dimensional one, appropriate for plate.

The existence and uniqueness of the solution of a system of nonlinear partial differential equations arising from the modeling of current carrying thermoelastic plate-strip in a longitudinal magnetic field is proven.



## REFLECTION AND REFRACTION OF MAGNETOELASTIC WAVES AT THE INTERFACE OF TWO FERROMAGNETIC SEMI-INFINITE SPACES

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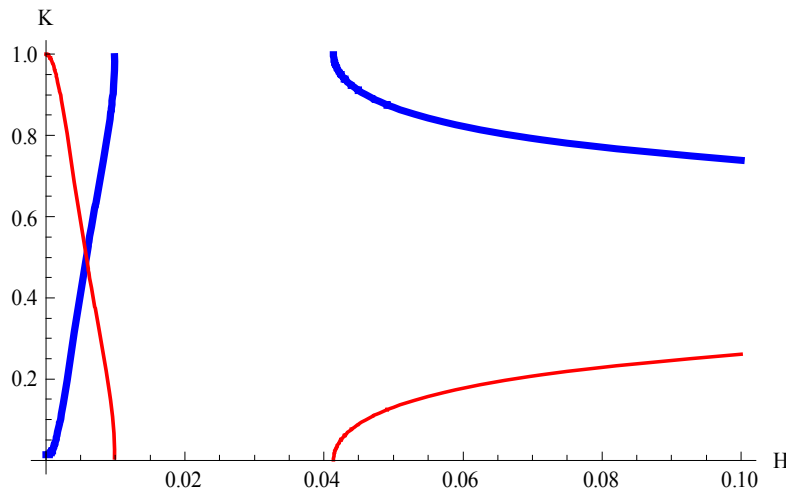
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In this work a model is presented and used to explore the spin (magnon) and antiplane elastic (phonon) wave interaction effects in piecewise homogeneous ferromagnetic spaces. The magnetic polarization vector is perpendicular to the wave propagation direction. The space is in an external homogeneous magnetic field, the direction of which coincides with direction of the initial magnetization vector. Waves are generally reflected at an abrupt discontinuity such as the interface between two different media. The problem of reflection and transmission of magnetoelastic waves is discussed when magnetoelastic space consists of two different, perfectly joined semi-spaces.

The existence of a new type of Accompanying Surface Magnetoelastic (ASM) waves stimulated by magnetostriction is shown. These waves are localized to the interface between two ferromagnetic media and accompany the reflection and transmission waves. The reflected, transmitted and ASM waves are strongly depend on frequency and angle of the incident wave, as well as on the physical parameters of ferromagnetic semi-spaces.

Numerical results show that an applied external magnetic field also has a strong influence on the magnitudes of these waves.



**Figure 1:** Dependence of magnitude of reflection  $K_R$  and transmission  $K_T$  coefficients on dimensionless magnetic field  $H$ . Red color corresponds to  $K_R$ ,

Figure 1 represents the behavior of absolute values of reflected  $|K_R|$  and transmitted  $|K_T|$  of elastic waves coefficients on applied magnetic field when dimensionless frequency  $\Omega = 0.1$  and incident wave angle  $\theta_i = 0.01$ .

Numerical calculations demonstrate that: (i) there is a range of magnetic fields over which both reflection and transmission coefficients totally vanish, and (ii) the reflection coefficient and the transmission coefficient have a complementary dependence on magnetic field; when one increases the other decreases a corresponding amount.



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