Curriculum Vitae

NAME: Romesh C. Batra

U. S. CITIZEN
Honorary Member - ASME
Fellow - ASME, ASEE, AAM, SES, USACM
Member – ASCE

PRESENT POSITION:

University Distinguished Professor and Clifton C. Garvin Professor
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RELEVANT WEBSITES:

Home page: https://www.sites.beam.vt.edu/batra/

List of former doctoral students:
http://genealogy.math.ndsu.nodak.edu/id.php?id=105522

Scholar profile:
https://scholar.google.com/citations?user=QpAXXoEAAAAJ&hl=en

Lectures on Continuum Mechanics:
https://www.youtube.com/watch?v=HkNuNE1_de4

Video prepared by the ASME and played at the Honorary Membership Award Ceremony:
https://www.youtube.com/watch?v=iVX8kHLzruA&list=PLq-Gm0yRYwTg9gY-xhVpZ5LoctJVi-m2S

EDUCATION:

B.Sc. Mechanical Engineering, (Gold Medalist, 1st rank in 3 states (the Indian Institution of Engineers honored this accomplishment with a Plaque and a Monetary Award)),Thapar Institute of Engineering and Technology, Patiala, India, 1968

M.A.Sc. University of Waterloo, Waterloo, Canada, 1969

Ph.D. The Johns Hopkins University, Baltimore, USA, 1972

RESEARCH INTERESTS:

Material Failure at High Strain Rates, Penetration & Impact Problems, Functionally Gradient Materials/Structures, Molecular Mechanics/Dynamics Simulations of Nanostructures, Smart structures/Piezoelectric materials

ACADEMIC EXPERIENCE:

4/10/1994-Present, University Distinguished Professor and Clifton C. Garvin Professor of Engineering Science and Mechanics, Virginia Polytechnic Institute & State University (Virginia Tech)
8/1994-4/9/2019, Clifton C. Garvin Professor of Engineering Science and Mechanics, Virginia Tech
1981-94, Professor; 1977 -'81, Assoc. Prof.; 1974 -'76, Assistant Prof., Univ. of Missouri – Rolla (UMR; now called Missouri University of Science & Technology)
1976 - '77, Assistant Professor, The Univ. of Alabama, Tuscaloosa
1973-74, Research Associate, McMaster University, Hamilton, Canada
1972-73, Postdoctoral Associate, The Johns Hopkins University, Baltimore

VISITING APPOINTMENTS:

Dec. 2017	Fulbright Specialist in Solid Mechanics, Amrita Vishwa Vidyapeetham, Coimbatore, India
Dec. 2013	Fulbright Specialist in Solid Mechanics, Thapar University, India
August 2016	Nanjing University of Science and Technology, Nanjing, China
May 2015	Universidad del Norte, Barranquilla, Colombia
May 2014	Yangzhou University, Yangzhou, China
May 2010	Universidad de Chile, Santiago, Chile
May 2009	Institute of Metals Research, Chinese Academy of Sciences, Shenyang, China
1998 – 2004	Several short term visits to University di Roma "La Sapienza" Rome, Italy
Summer 2003	von Humboldt Awardee, Technical Univ. of Berlin, Germany
7/'99-1/2000	von Humboldt Awardee, Technical Univ. of Berlin, Germany
May 1990	Jefferson-Smurfit Fellow, Univ. College, Dublin, Ireland
June 1987	Visiting Prof., Technical Univ. of Berlin, Germany
1/'85-6/'85	Visiting Prof., Univ. of Minnesota
9/'83-8/'84	Senior Research Fellow (Inter-personnel Government Assignment), Army Research Lab., Aberdeen, MD
5/'83-8/'83	Visiting Scientist, Sandia National Lab, NM
July 1980	Visiting Professor, Univ. of Pisa, Pisa, Italy

HONORS & AWARDS:

(a) International/National Level

2019	Belytschko Medal from the US Association of Computational Mechanics for "outstanding computational work for analyzing Adiabatic Shear Bands, proposing modified- and smooth-symmetric particle hydrodynamics (MSPH/SSPH) basis functions, and the method of manufactured solutions for code verification." (**only VT faculty honored thus far by the USACM**)
2018	Special issue of the International J. of Mechanical Sciences honoring Romesh Batra on his 70th Birthday coedited by his two

former mentees, Maurizio Porfiri and Davide Spinello (https://doi.org/10.1016/j.ijmecsci.2018.02.023)

2018 Special symposium at the 18th US National Congress of Theoretical and Applied Mechanics honoring Romesh Batra, Chicago, 2018 (organized by his former Post-doctoral Fellow, Zhigang Wei, and his former mentee, Senthil S. Vel)

2018 Member – The National Academies of Sciences, Engineering and Medicine Panel on Mechanical Science and Engineering (Platform Mechanics team leader)

2017 Member – The National Academies of Sciences, Engineering and Medicine Panel for Lethality and Protection

2017 Fulbright Specialist in Solid Mechanics, Amrita Vishwa Vidyapeetham, Coimbatore, India, Dec. 2017 – Jan. 2018

2016 ASME (American Society of Mechanical Engineers) Robert Henry Thurston Lecture Award (It provides an opportunity for a *leader* in pure and/or applied science or engineering to present to the Society a lecture that encourages stimulating thinking on a subject of broad interest to engineers; **only VT faculty honored thus far**)

2016 Alumni Achievement Medal for Academic Excellence from the School of Engineering, University of Waterloo, Canada

2016 Hind Rattan (Jewel of India) Award from the Non-Residents of India (NRI) Welfare Society for outstanding lifelong accomplishments in recipient's field. Every year, the Society honors, on eve of India's Republic Day, 1 NRI for nearly 1 Million NRIs. *Out of 30 persons honored with the award on 25 January 2016, only 4 were university professors*

2015 ASME Honorary Member Award (An Honorary Member is a person who has made "*distinctive contributions*" to engineering, science, industry, research, public service, or other pursuits allied with and beneficial to the engineering profession; **3 awarded in 2015; only VT faculty honored thus far**)

2013 Fulbright Specialist in Nonlinear Solid Mechanics, Thapar University, Dec. 2013

2010 Selected for inclusion in the ISI List of Highly Cited Authors (less than 0.5% of researchers in a particular field are on the list)

2010 Lee Hsun Research Award from the Institute of Metals Research, Chinese Academy of Sciences (Lee Hsun Research Award honors outside scientists and engineering experts who have made great contribution to materials science and engineering and also are willing to irregularly attend long-term research collaboration, give lectures and participate in other activities)

2009 Engineering Science Medal from the Society of Engineering Science (**only VT faculty honored with it since the Society was founded in 1963**. The **Engineering Science Medal** is awarded in recognition of a singularly important contribution to Engineering Science. The recipient need not be a member of the Society, but becomes a lifetime member upon receipt of the medal)

2006	D.Sc. (Honoris Causa), Thapar University, India (one out of three persons honored with the degree since the University was founded in 1956)
2005	Honorary Professor, Lanzhou University of Technology, China
2004	Honorary Professor, Nanjing Univ. of Science & Technology, China
2002-2006	Member - The National Academies of Sciences, Engineering and Medicine Panel on Survivability & Lethality
2000	Eric Reissner Medal from the International Society of Computational Engineering Science (ICCES) for contributions to the Mechanics of Penetration (The MEDAL is given to a researcher, from anywhere in the world, in recognition of her/his contributions to any area germane to the ICCES (International conference on Computational and Experimental Engineering and Sciences), and in recognition of her/his services to ICCES. This award honors Professor Eric Reissner, who for nearly 60 years at MIT and at University of California-San Diego (UCSD), played a significant role in educating several generations of students in the areas of theoretical, applied, and computational mechanics)
1996-2000	Member - The National Academies of Sciences, Engineering and Medicine Panel on Armor & Armaments
1992	Recipient, Alexander von Humboldt Award for Senior Scientists (The award is granted in recognition of a researcher's entire achievements to date to academics whose fundamental discoveries, new theories, or insights have had a significant impact on their own discipline and who are expected to continue producing cutting-edge achievements in the future)

(b) State Level

2011	Virginia Outstanding Scientist Award (https://www.smv.org/storage/app/media/PDFs/virginiasoutstandingscientists.pdf)
2010	SCHEV (State Council of Higher Education of Virginia) Outstanding Faculty Award (http://www.schev.edu/index/institutional/outstanding-faculty-awards/award-recipients/previous-award-recipients)

(c) Fellowships of Professional Societies

2011	Fellow - US Association of Computational Mechanics
1998	Fellow - Society of Engineering Science, Inc. (in recognition of his many contributions in continuum mechanics and nonlinear elasticity, particularly in the dissipation phenomenon in solids)
1992	Fellow - American Society of Engineering Education
1991	Fellow - American Academy of Mechanics (in recognition of his outstanding contributions to research and leadership in Mechanics)
1990	Fellow - American Society of Mechanical Engineers
1993	Elected to the Johns Hopkins Society of Scholars

(d) Plenary/Memorial Lectures

2018	Structural Engineering Convention, Jadavpur University, Kolkata, India, December (http://sec18ceju.in/)
2015	B. Kannesh Memorial Lecture, 60th Congress of the Indian Society of Theoretical and Applied Mechanics (ISTAM), Jaipur, India
2014	B. R. Seth Memorial Lecture, 59th Congress of the ISTAM, Bangalore, India
2014	Plenary speaker, 4th National Symposium on Mechanics of Materials and Continuum Structures: Experimental, Numerics and Theoretical Modeling – SMEC**,** Bogotá, Colombia
2014	Plenary Lecture, 1st Int. Conference on Mechanics of Composites, Stony Brook Univ., Long Island, NY
2013	Plenary Lecture, 17th Int. Congress on Composite Structures, Porto, Portugal
2012	B. Kannesh Memorial Lecture, 57th Congress of the ISTAM, Pune, India
2012	Plenary Lecture, International Congress of Computational Mechanics and Simulations, Hyderabad, India
2000	Lecturer - Southwest Mechanics Series

(e) *University/College Level*

2016	Alumni Award for Excellence in Graduate Advising
2015	Leadership in Scholarship – Award, Department of Biomedical Engineering and Mechanics
2007	College of Engineering Dean’s Award for Excellence in Service
2005	College of Engineering Alumni Award for Outreach Excellence (inaugural year of Award)
2004	Alumni Award for Excellence in Research
2003	Frank J. Maher Outstanding Faculty Award, Department of Engineering Science and Mechanics
1997	College of Engineering Dean's Award for Excellence in Research (inaugural year of Award; 3 faculty out of nearly 300 are honored every year)
1993	'92, '91, '90, '89, '88, '87, Faculty Excellence Award, Missouri University of Science and Technology (MUST)
1986	Halliburton Excellence Award, School of Engineering, MUST

(f) *Professional Societies*

2003-2005	Secretary, American Academy of Mechanics (AAM)
2002-2006	Member - Awards Committee, AAM
1996	President, Society of Engineering Science (SES)
1990-1996	Member – Board of Directors, SES
1996-2000	Chair, Elasticity Committee, American Society of Mechanical Engineers

(g) *Award for Technical Paper*

1988 Jai Krishna Award from the Indian Society of Earthquake Technology for the paper "Seismic Response of a Multistory Building Supported on Piles and a Nonlinear Soil'' coauthored with Ph.D. student, J. U. Khandoker.

TEACHING AWARDS:

- SCHEV Outstanding Faculty Award mentioned above
- Teacher of the Week, VT's Center for Instructional Development and Educational Research
- Dean's list of Outstanding Teachers, Virginia Tech, several semesters
- Outstanding Teaching Award, ($1,000 Professional Expenses) MUST, 1988
- Letter of Commendation for Excellence in Teaching, MUST, 1991
- Exceptional Teaching Effectiveness - Letter of Commendation, MUST, 1989
- 1977 Charles Henry Ratcliff Memorial Award for Excellence in Undergraduate Teaching in the Dept. of Aerospace Engr., Mech. Engr. and Engr. Mech., The Univ. of Alabama

Scholarship Statistics

Citation information
Google Scholar:
https://scholar.google.com/citations?user=QpAXXoEAAAAJ&hl=en
Date: 23 September 2021
No. of citations: 21,454
H-index = 77

Scopus:
https://www.mendeley.com/profiles/romesh-batra2/stats/
No. of citations: 15,864
H-index = 64

Number of Ph.D. students mentored to completion = 41 (37 solo advisor and 4 co-advised; 1 student funded by Fulbright)
http://genealogy.math.ndsu.nodak.edu/id.php?id=105522
Number of M.Sc. students mentored to completion = 21
Number of undergraduate student researchers = 28

Number of Post-doctoral Fellows/Visiting Scholars = 66
Fulbright Scholars = 2
Scholars supported by Chinese Science Scholarship = 18
Scholars supported by home institutions (Thailand, Turkey, Iran, China, India) = 7

Number of text books = 1

Total number of papers in peer-reviewed journals = 461

No. of papers co-authored with 41 Ph.D. Students = 156 (Avg. = 3.8)
No. of papers co-authored with 21 M.Sc. Students = 20 (Avg. = 1)
No. of papers co-authored with undergraduate students = 5
No. of papers co-authored with students in my 6xxx level classes = 8
No. of book chapters = 9

The complete list of peer-reviewed journal papers is given in a different section below.

SIGNIFICANT CONTRIBUTIONS IN RESEARCH:

Dr. Batra's research group has made outstanding contributions in the following areas of Applied Mechanics.

A. Material Failure under Extreme Loadings

A challenging problem in the failure mechanics of materials is developing a science-based mathematical model that incorporates most of the relevant physics and accurately predicts how material, geometric and loading parameters influence the failure under a variety of loads. In 1983, Drs. Wright (Army Research Laboratory) and Batra collaborated in proposing a model for the failure of structures subjected to shock/blast loads like those produced by improvised explosive devices (IEDs). For these loads, failure usually occurs due to shearing (or sliding) of one part of the body over the other like slipping of a car on an ice sheet. Wright and Batra developed a physics-based mathematical model of simple shearing deformations of a metallic (e.g., steel) block. These deformations are analogous to those produced in a highly viscous fluid (thick honey) enclosed between two parallel rigid plates separated by distance H in the vertical (y-) direction with the bottom plate kept fixed and the top plate moved with a uniform velocity V in the horizontal (x-) direction. After transients have died out, all particles move only in the x-direction and the velocity field varies linearly from zero at the bottom plate to velocity V at the top plate assuming that the material sticks to the plates. The average strain rate in the material is V/H; similar deformations occur in a viscometer and when dough in a bowl is steadily stirred with a spoon.

For very rapid deformations, failure occurs in several micro-seconds or at most a millisecond (ms) that is much smaller than the time taken to blink an eye. Heat generated due to plastic (or permanent) deformations of a ductile material like steel raises its temperature similar to what occurs in the "burning" of car tires sliding on ice or rubbing of hands on a cold day. The time for the heat to meaningfully dissipate from the plate boundaries to the surroundings is of the order of seconds.

Since real materials have defects that prevent deformations from smoothly varying in a body, Wright and Batra perturbed the solution to the above formulated problem to simulate effects of defects. This simple model has all the relevant physics needed to study the localization of deformation into thin regions or adiabatic shear bands. Indeed, the Wright-Batra model predicted the shear banding phenomenon. Interestingly, *the predicted time evolution of the shear stress at the band center that had not been reported prior to this work was subsequently confirmed by experimental observations.*

The mathematical model was subsequently refined by Batra who hypothesized that the material response (stress-strain or force-elongation relation) also depends upon strain gradients (i.e., deformations of 3 instead of 2 adjacent atoms situated on a straight line interact with each other). It makes computational analysis more involved, but gives the band width (thickness of the intensely deformed region of permanent or plastic strains) and the shear band initiation time independent of the domain discretization (often called finite element mesh size) used to numerically solve the problem. Elastic deformations are reversible (i.e., disappear upon unloading the body, e.g., those produced in a soft rubber or during pulling of one's skin), but plastic strains are permanent like a dent in a car panel. *Batra also proposed a shear band initiation criterion that has been adopted by several investigators, and included in computer codes. A few key accomplishments in this field are listed below.*

- Proposed adiabatic shear band (ASB) initiation criterion for high strain-rate deformations of thermo-elasto-visco-plastic materials. An ASB is a narrow region of intense plastic deformation that forms during high strain-rate deformations of many materials especially metals, and is a precursor to a crack
- Computed ASB width, ASB speed, and spacing between adjacent ASBs
- Delineated effects of heat conduction, strain gradients, and phase transformations in steels on ASB formation, and spacing between ASBs
- Determined impact speed for transition from brittle to ductile failure in pre-notched plates
- Developed a thermo-visco-plastic material model for considering strain hardening, strain-rate hardening and thermal softening suitable for incorporation in computer codes to analyze ASBs, deep penetration into thick targets, and plug formation in thin targets
- Developed in-house software to efficiently analyze ASB phenomenon
- Proposed and implemented in commercial software models for progressive damage and eventual failure of fiber-reinforced composites
- Developed mathematical and computer models for blast resistant light-weight sandwich structures
- Analyzed armor for protecting soldiers using gelatin as a surrogate material and computed behind the armor blunt trauma

A splendid tribute to and an unsolicited endorsement of a scientist's fundamental contributions are in other authors incorporating his/her work in their text books. Results on the failure of materials from Batra's team have appeared in at least the following 7 books/book chapters:

- N. Cristescu, *Dynamic Plasticity*, World Scientific, 2007 (Work cited on p. 410, 420, 433, 442)
- T. W. Wright, *The Physics and Mathematics of Adiabatic Shear Bands*, Cambridge University Press, 2002. (Sec. 9.2, pp. 212-218 are taken from Chen & Batra, *Int. J. Plasticity*, 1999; 8 other papers cited)
- Y. M. Haddad, *Mechanical Behavior of Engineering Materials, Vol. 2: Dynamic Behaviour and Intelligent Material Systems*, Kluwer, 2001 (4 papers cited)
- Y. Tomita, Simulation of Plastic Instabilities in Solid Mechanics, *Applied Mechanics Reviews*, Vol. 47, pp. 171-205, 1994 (Fig. 4.1, and 8 papers cited)
- Y. L. Bai and B. Dodd, *Adiabatic Shear Localization, Occurrence, Theories, and Applications*, Pergamon Press, 1992. (work cited or Figs. included on p. 178, 196, 197, 198, 205, 206, 207, 208, 211, 212, 217, 219, 220)
- T. Nicholas and A. M. Rajendran, Material Characterization at High Strain Rates, in *High Velocity Impact Dynamics*, (J. A. Zukas, Ed.), John Wiley & Sons, 1990. (Figs. 76, 77, 78 on p. 265, 267 and 268)
- S. Li and W. K. Liu, Meshfree Particle Methods, Springer, 2004 (3 papers cited)

B. Composites

B.1 Functionally graded materials for optimum failure load

Functionally graded materials (FGMs) are composites having continuous variation of material properties in one or more space directions that can be exploited to design structures with optimum spatial distribution of constituents for a specific application (many plants and organs of creatures share this property) and maximizing the failure load. These materials can now be easily fabricated using either 3-D printing or electron beam deposition. Examples of engineered structures include tiles used on space shuttles. These tiles have through-the-thickness composition gradually varying from 100% ceramic to 100% metal with the ceramic surface exposed to the atmosphere and the metallic one bonded to the shuttle. The ceramic resists the heat when the shuttle reenters the atmosphere. Many natural objects have material properties continuously varying throughout the structure; e.g., in a bamboo the concentration of fibers is highest on the outermost surface and least near the center. The enamel is the hardest bodily tissue covering the dental crown. Inner layers, dentin, cementum and pulp tissue become gradually softer.

Batra (Finite Plane Strain Deformations of Rubberlike Materials, *Int. J. for Numerical Methods in Engineering*, 15, 145-160, 1980), without using the phrase FGMs, analyzed large deformations induced in a pressurized cylinder made of an inhomogeneous material (e.g., an artery) and showed excellent agreement between numerical and analytical solutions. More recently, his group has tailored material properties to insure that the maximum stress in a cylinder and a sphere is nearly the same at every point thereby providing the lightest possible structure for synthetic arteries.

Lessons learned from designing simple structures are now being adopted for designing lightweight blast resistant armor to protect soldiers and infrastructure.

For designing lightweight functionally graded metallic structures resistant to impact and blast loads, one needs to understand crack propagation in an FGM. A commonly used postulate is that fracture initiation and propagation in a structure strongly depends upon the order of singularity in deformations (strains and stresses) near the crack-tip. One of the important results from Batra's group is that the inverse square-root singular solution available for homogenous (i.e., monolithic) materials is also applicable for FGMs. *This theoretical result was subsequently confirmed by other investigators through numerical solutions implying the accuracy of predictions from the mathematical model.*

Batra's group also found that the fracture toughness and the residual strength based on the rule of mixtures are noticeably higher than those based on the crack-bridging concept. When the fracture toughness is computed using the crack-bridging concept, the initial crack size strongly influences the slope of the crack growth resistance curve (R-curve; or the additional work done on the structure for the crack to propagate) especially during the initial stage of the crack growth. When the crack has grown so that the bridging zone has fully developed, the toughness becomes independent of the initial crack size. *A significant discovery is that the fracture toughness can be substantially increased for a crack growing from the ceramic-rich region into the metal-rich region.*

Some salient results are:

- Because of the noticeable effect of the initial crack size on the crack-resistance curve, the latter is not a material property
- By appropriately grading the thermal conductivity, the maximum tensile thermal stress in a thin FGM plate can be substantially reduced and the maximum magnitude of the compressive stress increased to maximize plate's load carrying capacity

- A zone of large compressive stress just away from the thermally shocked surface is developed during initial stages of the thermal shock
- Delineated the critical role of the temperature dependence of ceramic properties by showing that steady thermal stress intensity factor in an edge-cracked strip can exceed ceramic's fracture toughness and neglecting this temperature-dependence predicts an erroneous value of zero

Several results on FGMs are included in the following 9 books/book chapters:

- H.-S. Shen, Functionally Graded Materials, Nonlinear Analysis of Plates and Shells, CRC Press, 2011
- Issac Elishakoff, D. Pentaras and C. Gentilini, "Mechanics of Functionally Graded Material Structures", World Scientific, 2015
- H. Altenbach and G. I. Mikhasev (Eds.), Shell and Membrane Theories in Mechanics and Biology, From Macro- to Nanoscale Structures, Springer, 2015
- S. Thomopoulos, V. Birman and G. M. Genin (Eds.), Structural Interfaces and Attachments in Biology, Springer, 2013
- A. Ochsner, H. Altenbach and L. F. M. da Silva (Eds.), Materials with Complex Behavior II: Properties, Non-Classical Materials and New Technologies, 2012
- N. E. Shanmugam and C. M. Wang (Eds.), Analysis and design of plated structures, Vol. 2: Dynamics, CRC, 2007
- R. de Borst and T. Sadowski (Eds.), Lecture Notes on Composite Materials, Current Topics and Achievements, Springer, 2008
- I. E. Reimanis, Handbook of Advanced Materials: Enabling New Designs, J. K. Wessel (Editor), Wiley, 2004
- R. de Borst and H. A. Mang (Eds.), Comprehensive Structural Integrity, Fracture of Materials from Nano to Macro, Elsevier, 2003

B.2 Failure Analysis of Laminated Structures

Fiber-reinforced laminates are used as structural elements since for the same areal density (mass per unit surface area) they have the maximum strength in the fiber direction. Both fiber directions and volume fractions can be optimized (material tailoring problem solved) to acquire desired specific strengths in pre-specified directions. These require accurate mathematical models and efficient numerical and analytical techniques to accurately find loads that cause failure in laminated structures. A few salient results from Batra's group are listed below.

- Provided benchmark solutions, using the Eshelby-Stroh formalism for rectangular laminates with arbitrary boundary conditions on edges, to verify computational algorithms and establish the accuracy/validity of reduced-order models

- For a fiber-reinforced laminate with fiber directions in alternate layers perpendicular to each other, the transverse normal stress near clamped and traction free edges exhibits sharp gradients (or boundary layers) at interfacial points adjacent to the edges. No boundary layers are observed near simply supported edges
- Provided materially tailored designs/solutions for fiber-reinforced disks and cylinders, and cylindrical/spherical pressure vessels to have the minimum weight for prescribed loads
- Developed software to analyze delamination between adjacent plies, initiation and progression of damage at the constituent level, and degradation of material properties of the damaged constituent
- Analyzed mixed-mode delamination in sandwich structures due to water slamming loads typical of those experienced by a boat hull sailing at a high speed

Some of this work has appeared in the following five books.

- H. Abramovich, Intelligent Materials and Structures, De Gruyter Graduate, 2016
- G. Dvorak, Micromechanics of Composite Materials, Springer, 2013
- G. Jin, T. Ye and Z. Su, Structural Vibration: A uniform accurate solution for laminated beams, plates and shells with general boundary conditions, Springer, 2015
- Inderjit Chopra and Jayant Sirohi, Smart Structures Theory, Cambridge Aerospace Series, 2013
- H. Altenbach and W. Becker (Eds.), Modern Trends in Composite Laminates Mechanics, CISM Course and Lectures No. 448, ICMS, Springer, 2003

B.3 Failure detection and vibration control in laminated structures using piezoelectric patches

Piezoelectric materials produce electric current when stressed/deformed. They are commonly used for harvesting energy from structure's vibrations and monitoring structure's health (e.g., there are many such sensors imbedded in Goodwin Hall at VT) including impending failure. Challenging issues include optimizing their geometries and locations in a structure for maximizing patches' life span without sacrificing the information retrieved from them. Batra's group found that embedding patches in a laminated structure's interior to simultaneously exploit their normal and shear deformations increases patches' effectiveness, minimizes stresses induced in them, and maximizes their durability. Batra's team is probably the first one to develop non-linear material and numerical models for piezoelectric materials. Some other key results are summarized below.

- For verifying computational models, provided benchmark analytical solutions for 3-dimensional static and dynamic deformations of hybrid laminates with piezoelectric layers either embedded in or bonded to the major surfaces

- Optimized the polarization direction of piezoelectric patches to maximize their sensitivity
- Showed, through exact solutions of example problems, that the frequently used assumption of the linear through-the-thickness distribution of the electric potential should be modified to a parabolic distribution
- For electric potentials applied to the top and the bottom surfaces, the induced transverse electric displacement and the transverse shear stress exhibit boundary layers near edges of a thick laminate unless the edge is simply supported and electrically grounded

The work on piezoelectricity (or smart structures) is included in at least the following 4 books:

- H. Abramovich, Intelligent Materials and Structures, De Gruyter Graduate, 2016
- Inderjit Chopra and Jayant Sirohi, Smart Structures Theory, Cambridge Aerospace Series, 2013
- Q.-H. Qin, Advanced Mechanics of Piezoelectricity, Springer, 2013
- J. Yang, An Introduction to the Theory of Piezoelectricity, Springer, 2005

B.4 Improved Mathematical, Computational and Failure Models of Laminated Structures

The analysis of 3-dimensional deformations of laminated structures under shock loads typically produced by an improvised explosive device is computationally very expensive. Reliable plate/shell theories reduce both the computational cost and the man-hours needed for the analysis. A significant challenge has been to ensure that the applied loads are correctly modeled. Vidoli and Batra have surmounted this by using a mixed-variational principle in formulating theories for plate-like structures. A few accomplishments are listed below.

- Characterized delamination failure modes in curved structures due to slamming loads experienced by a boat hull sailing at high speed
- Showed that the predicted time for failure initiation using plate theories is a few nano-seconds less than that found using 3-dimensional analysis
- Demonstrated that clamping an interior structural point to stay stationary significantly affects structure's deformations

C. Nano-reinforcements for increasing structures' failure load

The availability of carbon nanotubes (CNTs), single-layer graphene sheets and similar nano-structures has revived interest in analyzing their mechanical properties both for use as monolithic structures and as reinforcements. Besides the dependence upon the molecular mechanics/dynamics (MM/MD) potentials the deduced mechanical properties depend upon which quantity (e.g., the strain energy or the frequency of vibration or the bending stiffness) for the nanostructure is equated to that of the equivalent continuum structure (ECS). The ECS properties are employed in a micro-mechanics theory to deduce mechanical properties and failure characteristics of a practical size structure.

Some of the key contributions in these fields are:

- Analyzed buckling failure mode and the corresponding load of gold nanowires, and single-wall CNTs
- Computed failure load and crack propagation speed in single-layer graphene sheets
- Determined wall thickness of a single-wall CNT and of a single layer graphene sheet from MM and MD simulations of axial and bending deformations, and different modes of vibration
- Developed techniques to compute binding affinity and diffusion of flavor compounds into epoxies

D. Micro-electro-mechanical systems as sensors

For micro-electro-mechanical systems (MEMS) besides the usual mechanical and the Coulomb forces one should consider either the van der Waals or the Casimir force between adjacent electrical conductors. Since these forces are nonlinear functions of the distance between points on the two conductors, the problems become highly nonlinear and more challenging to analyze. This work is critical for designing tiny needles to inject fluids into living organisms without stimulating nerve cells. Furthermore, MEMS are used as sensors and actuators.

Batra's team accomplishments in this field include:

- Proposing simpler mathematical and computational models for studying pull-in instabilities
- Delineating characteristics of elliptical devices
- Suggesting MEMS as thermal sensors

The work has appeared in at least the following two books:

- B. Magrab, Vibrations of Elastic Systems with Applications to MEMS and NEMS, Springer, 2012
- Evgeni Gusev, Eric Garfunkel and Arthur Dideikin (Eds.), Advanced Materials and Technologies for Micro/Nano-Devices, Sensors and Actuators, Springer, 2009

E. Computational Methods and Algorithms

Computational algorithms are now being used to design innovative prototypes of industrial components, prosthetics and drugs to minimize their cost. Verified and validated computer software enables one to explore design space that is generally not experimentally accessible. It also reveals phenomena in the interior of a structure that often cannot be observed in tests. In response to a question from a student in one of his graduate level courses, Batra proposed a technique to verify that the code correctly solves partial (or ordinary) differential equations for a class of initial-boundary-value problems for which the code was developed. The adequacy of the relevant physics included in the mathematical model can only be established by comparing predictions from it with test findings for a range of values of pertinent variables.

Key contributions include:

- Proposing the method of manufactured solutions to verify a computer code
- Developing software for studying failure in structures
- Assisting *companies (*paper mills, photocopying machines, and tire) *improve upon the design of roll covers* by developing a software for nonlinear elastic rubber-covered rolls
- Proposed modified smooth particle hydrodynamics (MSHP) and symmetric smooth particle hydrodynamics (SSPH) methods for efficient numerical analysis of structural failure under shock loads

Books in which the work has appeared include the following:

- M. B. Liu and G. R. Liu, Particle Methods for Multi-Scale and Multi-Physics, World Scientific, 2016
- R. Trobec and G. Kosec, Parallel Scientific Computing: Theory, Algorithms and Applications of Mesh Based and Meshless Methods, Springer, 2015
- S. N. Atluri and Shenping Shen, The Meshless Local Petrov-Galerkin (MLPG) Method, Tech Science Press, 2002
- G. R. Liu and Y. T. Gu, An Introduction to Meshfree Methods and their Programming, Springer, 2005

Other books in which Batra's work has appeared:

- M. M. Carroll and M. A. Hayes (Eds.), Nonlinear Effects in Fluids and Solids, Plenum Press, 1996
- D. Iesan, Thermoelastic Models of Continua, Springer, 2004

GRADUATE STUDENTS' RESEARCH SUPERVISION:

Doctoral (completed):

(a) University of Missouri-Rolla (now called Missouri Univ. of Science & Technology) [The Engineering Mechanics Dept. started admitting Ph.D. students in 1984. Batra helped in writing the proposal for initiating the Ph.D. program. Bapat and Khandoker were enrolled in Civil Engineering but worked with me for their Ph.D. degrees]

1. C. N. Bapat, 1983, "Plane Strain Deformations of Viscoelastic Rubber Covered Rolls"
   Current position: *Retired, CA*

2. J. U. Khandoker, 1984, "Seismic Response of a Multistory Building Supported on Piles and a Nonlinear Soil"
   Current position: *unknown*

3. Pei-Rong Lin, 1988, "An Analysis of Steady State Penetration Problems by the Finite Element Method"
   Deceased, 2017

4. De-Shin Liu, 1989, "Dynamic Adiabatic Shear Band Development in Plane Strain Deformations of a Viscoplastic Material"
   Current position: *Distinguished Professor of Mechanical Engineering, National Chung Cheng University, Taiwan*

5. C. H. Kim, 1989, "Shear Strain Localization Phenomenon in Viscoplastic Materials"
   Current position: *unknown*

6. T. Gobinath, 1990, "Finite Element Solution of Axisymmetric Penetration Problems"
   Current position: *Manager, Goodyear Tire, Akron, OH*

7. R. Jayachandran, 1991, "Analysis of Steady State Axisymmetric Penetration Problems by the Finite Element Method Using a Mixed Formulation"
   Current position: *Engineer, Global Safety Systems Engineering, Ford Motor Co.*

8. K.-I. Ko, 1991, "An Adaptive Mesh Refinement Technique for Two-Dimensional Problems and its Application to the Analysis of Shear Bands"
   Current position: *unknown*

9. J. Hwang, 1992, "Analysis of Dynamic Shear Bands in Plane Strain Compression of Dipolar Thermoviscoplastic Materials by Using an Adaptively Refined Mesh"
   Current position: *Professor, Korean Air Force Institute*

10. X. Chen, 1993, "Finite Element Analysis of Axisymmetric Deformations of Thick Thermoviscoplastic Targets"
    Current position: *Entrepreneur*

11. X.-T. Zhang, 1993, "Finite Element Analysis of Dynamic Shear Bands in 2-D and 3-D Deformations of Thermoviscoplastic Materials"
    Current position: *Manager, Ford Motor's research center, Nanjing, China*

(b) Virginia Tech [since 1994]

12. X.Q. Liang, 1997, Dynamic Response of Linear/Nonlinear Laminated Structures Containing PZT Laminas"
Current position: *unknown*

13. S.S. Vel, 1998, "Analytical Solutions for the Deformation of Anisotropic Elastic and Piezothermoelastic Laminated Plates"
Current position: *Arthur S. Wiley Professor, University of Maine; winner of American Academy of Mechanics Young Investigator Award*

14. N.A. Jaber, 2000, "Finite Element Analysis of Thermoviscoplastic Deformations of an Impact Loaded Prenotched Plate"
Current position: *Senior Engineer, GE Oil & Gas, Saudi Arabia*

15. T.S. Geng, 2002, "Enhancement of the Dynamic Buckling Load and Analysis of Active Constrained Layer Damping with Extension and Shear Mode Piezoceramic Actuators"
Current position: *unknown*

16. H.-K. Ching, 2002, "Solution of Linear Elastostatic and Elastodynamic Plane Problems by the Meshless Local Petrov-Galerkin Methods"
Current position: *Research Engineer, Westinghouse, Pittsburg, PA*

17. M.H. Lear, 2003, "Numerical Simulation of Adiabatic Shear Bands and Crack Propagation in Thermoviscoplastic Materials"
Current position: *Head, Mechanical Systems and Design Department, The Pennsylvania State University, Applied Research Lab*

18. B.M. Love, 2004, "Multiscale Analysis of Failure in Heterogeneous Solids under Dynamic Loading"
Current position: *Branch Chief, Army Research Lab, Aberdeen, MD*

19. A. Caba, 2005, "Characterization of Carbon Mat Thermoplastic Composites: Flow and Mechanical Properties"
Current position: *Research Engineer, ATK, Radford, VA*

20. N.M. Hassan, 2005, "Damage Development in Static and Dynamic Deformations of Fiber-Reinforced Composite Plates"
(Married name – Hussein)
Current position: *Associate Professor, American University of Sharjah, Sharjah, United Arab Emirates*

21. M. Porfiri, 2006, "Analysis by Meshless Local Petrov-Galerkin Method of Material Discontinuities, Pull-in Instability in MEMS, Vibrations of Cracked Beams, and Finite Deformations of Rubberlike Materials"
Current position: *Professor, New York University, NY; 2010 Brilliant Ten by Popular Science; Winner of 3 ASME Medals & numerous other awards*

22. D. Spinello, 2006, "Instabilities in Multiphysics Problems: Micro- and Nano-Electromechanical Systems and Heat-Conducting Thermo-Elastoviscoplastic Solids"
Current position: *Tenured Associate Professor and Assistant Department Head, University of Ottawa, Canada*

23. A. Sears, 2006, "Carbon Nanotube Mechanics: Continuum Model Development from Molecular Mechanics Simulations"
Current position: *Member- Composite Technology Research Group, Montana State University*

24. W. Jiang, 2008, "Simulations of Indentation at Continuum and Atomic Levels"
Current position: *Associate Professor, Huazhong University of Science and Technology, China*

25. A. G. Varghese, 2008, "Strain Localization in Tungsten Heavy Alloys and Glassy Polymers"
Current position: *Structural Engineer, Bridgestone Tire, OH*

26. S. S. Gupta, 2009, "Elastic Constants from Molecular Mechanics Simulations of Frequencies of Free-Free Single-Walled Carbon Nanotubes and Clamped Single-Layer Graphene Sheets"
Current position: *Tenured Associate Professor, Indian Institute of Technology-Kanpur, India*

27. A. Pacheco, 2009, "Molecular Mechanics Simulations of Instabilities in 3D Deformations of Gold Nanospecimens"
Current position: *Professor, Universidad Federico Santa Maria, Chile*

28. K. Das, 2009, "Analysis of Instabilities in Microelectromechanical Systems and of Local Water Slamming"
Current position: *Technical Support Engineer, Simulia, Providence, RI*

29. G. Gopinath, 2011, "Progressive damage and failure of unidirectional fiber reinforced laminates under impact loading with composite properties derived from a micro-mechanics approach"
Current position: *Structures Engineer, Pratt & Whitney, CT*

30. J. Xiao, 2013, "Local Water Slamming of Nonlinear Elastic Sandwich Hulls, and Adiabatic Shear Banding in Simple Shearing Deformations of Thermo-elasto-visco-plastic Bodies"
Current position: *Research Engineer, Global Engineering & Materials, Princeton, NJ*

31. Alireza Chadegani, 2013, "Hypervelocity Impact on Thermoviscoplastic Solids"

Current position: *Simulia R&D CS Mechanics Technology Manager, Providence, RI*

32. G. O. Antoine, 2014, "Computational Design of Transparent Polymeric Laminates subjected to Low-velocity Impact"
Current position: *Stress Engineer, Chez APCO Technologies SA, Lausanne, Switzerland*

33. A. I. Khan, 2015 (Co-advisor with Rakesh K. Kapania, AoE), "Progressive Failure Analysis of Laminated Composite Structures". (*Degree in AoE*)
Current position: *Senior Composites Engineer, ESE Industries, Atlanta, GA*

34. Bikramjit Mukherjee, 2016 (Co-advisor with David A. Dillard, BEAM), "Interfacial debonding from a sandwiched elastomer layer"
Current position: *Sr. Engineer, Dow Chemical*

35. Priyal Shah, 2017 "Computational Analysis of Elastic Moduli of Covalently Functionalized Carbon Nanomaterials, Infinitesimal Elastostatic Deformations of Doubly Curved Laminated Shells, and Curing of Laminates"
Current position: *Engineer, Advance Micro-Devices*

36. Qian Li, 2017 (Co-advisor with David A. Dillard, BEAM), "Finite Deformations of Fiber-Reinforced Rubberlike Solids, and of Adhesively Bonded T-peel Joints"
Current position: *Engineer, Cooper Tires*

37. Unchalisa Taetragool, 2017, "Optimal parameters for doubly curved sandwich shells, composite laminates, and atmospheric plasma spray process"
Current position: *Assistant Professor, King Mongkut's University of Technology Thonburi, Thailand*

38. Arka Prabha Chattopadhyay, 2018, "Free and Forced Vibration of Linearly Elastic and St. Venant-Kirchhoff Plates using the Third Order Shear and Normal Deformable Theory"
Current position: *Research Assistant Professor, Marshall University, Huntington, West Virginia*

39. Berkan Alanbay (Co-advisor with R. K. Kapania, AoE), 2020, "Free Vibrations and Static Deformations of Composite Laminates and Sandwich Plates using Ritz Method"
Current position: *Research Associate, Virginia Tech*

40. Lisha Yuan, Optimum First Failure, 2021, "Loads of Sandwich Plates/Shells and Vibrations of Incompressible Material Plates"

Current position: *Research Engineer, Bridgestone USA*

41. Balachandar Guduri, 2021, "Adaptive Process Control for Achieving Consistent Mean Particles' States in Atmospheric Plasma Spray Process".
Current position: *Research Associate, VTTI, Virginia Tech*

(In progress):

Monica Dhinde
Dongho Kim
Kesna Fairclough
Christian Mathew

Masters (Completed):

(a) University of Missouri-Rolla (now called Missouri Univ. of Science & Technology)

1. M. Hilgers, 1988, "Finite Plane Strain Thermomechanical Rolling Contact Problem for a Nonlinear Viscoelastic Cylinder"
Current position: Professor, Information Science & Technology, MUST
2. A. Adam, 1991, "Effect of Viscoplastic Flow Rules and Transverse Isotropy on Steady State Penetration of Thick Targets"
Current position: retired as Senior General Manager, Mahindra & Mahindra, India
3. L. D. Wang, 1993, "Analysis of Dynamic Shear Bands Under Combined Loading"
4. K. Ghosh, 1994, "Shape Control of Plates Using Piezoceramic Elements"
5. C. Adulla, 1994, "Effect of Prior Quasistatic Loading on the Initiation and Growth of Dynamic Adiabatic Shear Bands"

(b) Virginia Tech

6. N. V. Nechitailo, 1995, "Finite Element Analysis of Failure Modes in Dynamically Loaded Pre-Cracked Steel Plates"
Current position: *Senior Engineer, Naval Surface Warfare Center - Dahlgren*
7. D. J. Rattazzi, 1996, "Analysis of Adiabatic Shear Banding in a Thick-Walled Steel Tube by the Finite Element Method"
8. J. B. Stevens, 1996, "Finite Element Analysis of Adiabatic Shear Bands in Impact and Penetration Problems"
Current position: *Engineer, Proctor & Gamble, Cincinnati, OH*
9. J. G. Land, 1996, "An Axisymmetric Finite Element Solution for Elastic Wave Propagation through Threaded Connections" (Co-advisor: Ron Kriz)
Last known position: *Engineer, Ingersoll-Rand*

10. R. Gummalla, 1998, "Effect of Material and Geometric Parameters on Deformations of a Dynamically Loaded Prenotched Plate"
Current position: *Engineer, Proctor & Gamble, Cincinnati, OH*
11. A. Phillip, 2001, "Finite Element Analysis of a Rotor-Shaft System". (Co-advisor: Norm Dowling)
12. L. Placidi, 2002, "Solution of St.-Venant's and Almansi-Michell's Problems"
13. W. Ballew, 2004, "Taylor Impact Test, and Penetration of Reinforced Concrete Targets by Cylindrical Reinforced Rods"
14. J. E. Thompson, 2004, "Compaction and Cure of Resin Film Infusion Prepregs"
Current position: *U.S. Army*
15. S. Romano, 2005, "Three-dimensional Transient Analysis of Crack Propagation from a Void in a Thermoelastoviscoplastic Rectangular Plate", degree from the Univ. of Catania, Italy (Work done at VT, and 1 paper co-authored by Romano and Batra)
16. G. L. Iaccarino, 2006,"Analytical Solution of Two Traction-Value Problems in Second-Order Elasticity"
17. F. Bosco, 2009, "Mechanical Properties of Carbon Nanotubes", Degree from the Tech. Univ. of Denmark (Work done at VT, 2 papers co-authored by Gupta (doctoral student), Bosco and Batra)
Current position: *CEO, His own company*
18. J. E. Callahan, 2011, "Analysis of Composite Helmet Impact by the Finite Element Method" (*Degree in AoE*; Co-advisor: C. Woolsey)
Current position: *Engineer, GE, Baltimore, MD*
19. M. Rufinelli, 2016, "Optimum Damping of Beam Vibrations using Piezoceramic Transducers"
20. J. Fariborz, 2018, "Free Vibration of Bi-directional Functionally Graded Material Circular Beams using Shear Deformation Theory employing Logarithmic Function of Radius" (*Degree in ME*)
Current position: *Doctoral Student, Georgia Tech*
21. D. Burns, Analysis of Static and Dynamic Deformations of Laminated Composite Structures by the Least Squares Method.

Undergraduate seniors or Research Experience for Undergraduates:

At Virginia Tech

1. Deepti Verma, MSE, IIT-Kanpur, India (co-authored refereed journal paper # 381 with Gupta and Batra), 2012
2. G. Garcia, MSE, France (co-authored refereed journal paper # 234 with Marur, Loos and Batra), 2003
3. M. E. Malsbury, ME (co-authored refereed journal paper # 222 with Jaber and Batra), 2002

4. N. M. Wilson, ME (co-authored refereed journal paper # 152 with Batra), 1998
5. Pranav Agrawal, ME, IIT-Kanpur (co-authored refereed journal paper # 403 with Gupta and Batra; currently Ph.D. student at U. Waterloo), 2012
6. Casey Costa, ESM, 2013
7. Esha Kapania, General Eng'g, UVA, 2013 (studying for M.D., Chicago)
8. Armanj Hasanyan, ESM, 2013 (Earned Ph.D. from the Univ. of Michigan in 2018; now Post-doc at Cal Tech)
9. Derek Jones, ESM, 2013
10. Zaki Hussain, ESM, 2010-2011 (went to pursue Ph.D. at USC)
11. Brian Allen, ESM, 2008
12. M. Carrara, ESM, 2001-2002
13. Chris Scheu, ESM, 2000
14. Andy van Dooren, ESM, 1997
15. Jeremy Potter, ESM, 1997
16. J. Salmanoff, ESM, 1996
18. Regina Parkerson, 1996
19. Collin McClain, MSE, 2014
20. Shantanu Jain, ME, Thapar Univ., India, 2008
21. Salil Anand, ME, Thapar Univ., India, 2008
22. Akshay Dahiya, ME, IIT-Ropar, 2016 (pursuing Ph.D. at VT)
23. Michael McNamee, MSE, 2015-2016 (Senior Design)
24. Domonique Corey, MSE, 2015-2016 (Senior Design)
25. Gerald Boadu, MSE, 2015-2016 (Senior Design)
26. Tiara McDonald, MSE, 2015-2016 (Senior Design)
27. Stuti Budhiraja, Indira Gandhi Women College of Engineering, ME, 2017
28. David Gardiner, ESM, 2017 (Admitted to VT AoE Graduate Program, 2018)

POSTDOCTORAL RESEARCH ASSOCIATES & VISITING SCHOLARS:

(a) University of Missouri-Rolla (now called Missouri Univ. of Science & Technology)

1. Zhu, Zhen-Guo, Ph.D.(1988) Rutgers Univ., NJ (4/89 - 6/92)
2. Kim, Chang-Ho, Ph.D.(1989) Univ. of Missouri-Rolla, (5/89 - 5/90)
3. Wang, Yiming, Ph.D.(1991) Rutgers Univ., NJ (4/91-3/92)
4. Zhang, Jianping, Ph.D.(1991) Univ. of Pittsburgh, PA (9/91-8/92)
5. Spector, A. A., Ph.D.(1991) Moscow Academy of Sciences (6/92-9/93)
6. Kadic-Galeb, Aida, Ph.D.(1981) Lehigh Univ., PA (4/92-3/93)
7. Wu, Li, Ph.D.(1989) Tsinghua University, China (6/92 - 3/94)
8. Ru, Chong-Qing, Ph.D.(1988) Peking University, China (11/92 - 9/94)
9. Yang, Jiashi, Ph.D.(1993) Princeton University, NJ (9/93 - 8/94)
10. Zhang, Xiang-Tong, Shanxi Mining Institute, China (5/89 - 1/90)
11. Jin, Xuesong, Southwest Jiatong Univ., China (6/92 - 9/93)

(b) Virginia Tech

12. Huang, Yi-Nung, Ph.D. (1994) Univ. of Pittsburg (10/94-6/95)
13. Wang, J.D., Ph.D. (1992) Nagoya University, Japan (9/95-11/96)

14. Zhong, X., Ph.D. (1995) California Institute of Technology (8/95 -2/96)
15. Jin, Zhi-He, Ph.D. (1988) Tsinghua University, China (5/95-12/97)
16. Krishnaswamy, S., Ph.D. (1995) Univ. of California, Berkeley (1/96-8/97)
17. Chen, L., Ph.D. (1992) Univ. of Sci. & Tech. of China (12/96 - 9/99)
18. Oh, H.-S., Ph.D. (1996) Hanyang Univ., Korea (1/97-1/98)
19. Cheng, Z. Q., Ph.D. (1991) Univ. of Sci & Tech. of China (05/98-4/99)
20. Vidoli, S., Univ. of Roma, Italy (9/98-12/98; 2/00-7/00)
21. Yu, Jang-Horng, Ph.D. (1996) Univ. of Minnesota (1/99-8/99)
22. Vel, S.S., Ph.D. (1998) Virginia Tech (1/99-8/00)
23. Jiang, B., Ph.D. (1998) Tsinghua Univ. (12/99-5/01)
24. Marur, P.R., Ph.D. (1998) Auburn Univ. (2/02-1/03)
25. Wei, Z., Ph.D. (2001) Univ. of Sci. & Tech. of China (4/02-8/05)
26. Qian, L.F., Nanjing Univ. (4/02-4/03)
27. Jin, J., Nanjing Univ. (2/03-2/04)
28. Zhang, G.M., Ph.D. (2002), Univ. of Sci. & Tech. of China (6/03-3/07)
29. Li, S.R., Ph.D. (2003) Lanzhou University (2/04-1/05)
30. Yan, L.H., Ph.D. (2003) NUDT, China (5/04-11/04)
31. Wang, Z.C., (2004) Virginia Tech. (6/04-2/05)
32. Love, B.M., Ph.D. (2004) Virginia Tech. (1/05-6/05)
33. Ray, M.C., Ph.D. (1995) IIT Kharagpur (5/06-7/06; 5/07-7/07; 5/09 – 7/09; 5/10-7/10; 5/14-7/14)
34. Qin, Z. M., Ph.D. (2002) Virginia Tech (5/07-1/08)
35. Hasanyan, D., Ph.D. (1990) (5/07-8/07)
36. Hause, T., Ph.D. (1998) (6/07-8/07)
37. Jiang, W., Ph.D. (2008) Virginia Tech (7/08-6/09)
38. Varghese, A., Ph.D. (2008) Virginia Tech (10/08-9/09)
39. Nie, Guojun, Ph.D. (2002) Tongji Univ. (9/08-9/09)
40. Fang, H.W., Nanjing Univ. (9/08-9/09)
41. Zhang, M., Beijing Inst. Technology (9/08-9/09)
42. Artan, R., Ph.D. (1984) Istanbul Technical University (9/10-8/11)
43. Saidi, Alireza, Ph.D. (1998) S. Bahonar Univ. of Kerman, Iran.
44. Chen, Qiang, Nanjing Univ. (2/11-7/11)
45. Lu, Shufeng, Beijing Inst. Technology, (8/11-7/12)
46. Wen, Yaoke, Nanjing Univ., (11/11-10/12)
47. Kursun, Ali, Turkey (7/1/11-6/30/12)
48. Quy, Minh-Le, Hanoi Univ. of Science & Technology, Vietnam (9/11-5/12)
49. Banharnsakun, Anan, Ph.D. King Mongkut's Univ. Tech., Thonburi, Thailand (1/12-8/12)
50. Pacheco, A. A., Ph.D. (2009), Virginia Tech; Associate Professor, Universidad de Norte, Barranquilla, Colombia (8/11-7/12)
51. Pakel, H., Turkey (7/1/12-6/30/13)
52. Shen, Shang, Ph.D. (2012) Univ. of Akron (1/12 – 12/14)
53. Shi, Ruchao, Ph.D. (2013), Univ. of Sci. & Tech. China (3/15-3/16)
54. Kong, Shengli, Ph.D. (China), (4/15 – 3/16)
55. Lin, Enqiang, Ph.D. (2012) Tsinghua Univ. (1/15-12/16)
56. Qu, Yegao, Ph.D. (2014) Shanghai Jiao Tong University (3/15-3/17)
57. Pydah, Anup, Ph.D. (2016), Indian Institute of Technology-Chennai (4/16-4/19)

58. Patra, Puneet, Ph.D. (2016), Indian Institute of Technology-Kharagpur (6/16 – 5/17)
59. Zhao, Yuqing (Tongji Univ., China) (9/16-8/18)
60. Yu, Weili (China), (12/16 – 11/17)
61. Jia, Xiyu (China), (12/17 – 12/19)
62. Nie, Guojun, Ph.D. (2002) Tongji Univ., (1/18-1/19; 2nd time visitor)
63. Singh, Amit, Ph.D. (2016) Univ. of Minnesota (3/18-3/19)
64. Jain, Deepak, Ph.D. (2016) Thapar Univ. (3/18-3/19)
65. Sekaran, Mathiazhagan, Ph.D. (2017) Indian Institute of Space Research (1/18 – 1/19)
66. Ray, M. C., Ph.D. (1995) IIT Kharagpur (6/18 – 7/18; 6th time Visitor)
67. Islam, Md Rushdie Ibne, Ph.D. (2017) IIT Kharagpur (7/19-6/20)
68. Alanbay, Berkan, Ph.D. (2020) Virginia Tech (1/2021 –)

TEXT BOOK:

R.C. Batra, *Elements of Continuum Mechanics*, AIAA Publishers, 2006

Funded Research

Batra has been continuously funded since 1983 by the DoD in the area of material failure under extreme loading.

Total Batra's share = ~ $15M (~$11.5M at VT, ~$1.7M at MUST, ~$1.67M worth of CPU hours at National Supercomputing Centers while at MUST)

Funding Sources have included the NSF, ARO, ONR, AFoSR, NASA, Army Research Lab, and the following companies: Rolls-Royce, Air Bus, Boeing, Coca-Cola, Kennametal Inc., Ford, anonymous Health-care Company, Xerox Corp., Virginia's Advanced Manufacturing Center, Johns Hopkins University Applied Physics Lab

(a) at Virginia Tech since 1994 (Batra's share = $11.5M)

R. C. Batra, Modeling of implosion mitigation strategies for submerged composite and sandwich structures, 3/8/2021 – 3/7/2024, $105,002, ONR (Batra, 100%)

R. C. Batra, Optimal Blast Mitigating Sandwich Structures, 9/30/2020 – 2/28/2021, $680,000, ONR (Batra, 100%)

R. C. Batra, Blast Mitigation Strategies for Sandwich Structures with Fiber-reinforced Face sheets, 7/1/18 – 6/30/20, $269,684, ONR (Batra, 100%)

R. C. Batra, Modeling and Simulation of Ceramic Based Armor, $781,220, 9/29/17 – 9/28/19, US Army (Batra, 100%), [ITAR restricted]

R. C. Batra, Material Models for Fiber-Reinforced Structures, $273,381, 9/29/17 – 12/24/19, Private Company (Batra, 100%)

R. C. Batra, Underwater Implosion, Underwater Explosion, and Slamming of Marine Sandwich Structures, $934,481, 4/08-5/18, ONR (Batra, 100%)

R. C. Batra, Equation of State Evaluation for Solar Plus Program, The Johns Hopkins University Applied Physics Laboratory, $911,802 (flow through NASA), 1/1/09-9/15/17, (Batra, 100%), [ITAR restricted]

R. C. Batra, Modeling Impact Performance of Fiber-Based Armor Composite Laminates with Ceramic Back Plates, $460,000, 6/15/13 – 9/15/16, US Army (Batra, 100%)

D. A. Dillard, S. W. Case, R. C. Batra and S. H. McKnight, Adhesion Test Methods, Modeling and Durability, $351,959, 1/16 – 12/17, ONR (Batra, 25%)

R. C. Batra and S. O'keefe, Flavor Distortion through interaction of Chemicals in Fluids and Can coatings – Phase II, $185,336, 9/15-12/16, Public Company, (Batra, 90%)

S. O'Keefe and R. C. Batra, Flavor Distortion through interaction of Chemicals in Fluids and Can coatings, $199,617, 9/14-9/15, Public Company (Batra, 50%)

R. C. Batra, Distributed Memory High Performance Cluster, $174,198, ONR, 6/15/13-6/14/14, (Batra, 100%)

R. C. Batra and G. Pickrell, Closed Loop/Adaptive Process Control for Thermal Spray of Abradable Coatings, Rolls-Royce, $750,000 + $670,000 State Match, 12/1/09-11/30/15, (Batra, 50%)

R. K. Kapania and R. C. Batra, Progressive Failure Analysis Methodology for Laminated Composite Structures, EADS North America, $400,000, 1/1/10 – 9/30/14 (Batra, 50%)

R. C. Batra, Finite Element Analysis of Fiber-reinforced Tires, CenTire, $76,000, 8/15/13 – 8/14/15, (Batra, 100%; No overhead)

R. C. Batra, Physics Based Modeling of Thermal Spray Process, $91,000, 2/4/13-3/31/15, Commonwealth Center for Advanced Manufacturing, (Batra, 100%)

S. Case and R. C. Batra, N12A-T004 STTR Phase I: Bonded Joint Analysis Method, $32,000, 8/12-3/13, Global Eng'g & Materials, Inc., (Batra, 50%)

A. Druschitz, C. Williams and R. C. Batra, A Transformative Approach to Lightweight Armor: Metal-Ceramic Cellular Composite Castings, $74,915, 7/1/2012-6/30/2013, ICTAS, (Batra, 20%)

D. A. Dillard, R. C. Batra and R. Moore, Understanding and Controlling Factors Affecting Lens Demold Process, $401,972, 9/1/10-8/31/12, Private Company, (Batra, 33%)

T. Long, R. C. Batra et al., Army Materials Center of Excellence (MCOE) Program: Multilayered Technologies for Armored Structures and Composites: Teaming the Army Research Laboratories with Virginia Tech, $4.5M, 1/1/08-08/31/13, ARO, (Batra, 20%)

D. A. Dillard, D. C. Ohanehi, R. C. Batra and J. Dillard, Fracture of Adhesive Bonds under Mixed Mode Loading: Experiments in a Dual Actuator Load Frame and Numerical Simulations, $450,218, 08/01/08-07/31/11, NSF, (Batra, 25%)

R. C. Batra, Development of a Helmet Optimization Tool Using Computational Modeling, $147K, 10/21/09-8/29/10, The Johns Hopkins University Applied Physics Laboratory (Batra, 100%)

T. Campbell and R. C. Batra, Nano-Bio: The Next Transformative Convergence, $40K, 4/08-112/08, Humboldt Foundation (Batra, 50%)

R. C. Batra, Analysis of Injuries in Persons Wearing Soft Body Armor due to Impact Loads, $104,716, 5/9/07-6/30/08, ONR. (Batra, 100%)

R. C. Batra, Optimization, Alternative Materials and Improvement in Body Armor Shields, $270,000, 6/16/05-5/3/08, ONR (Batra, 100%)

R. C. Batra, Thermoelastic Dynamic Response of Advanced Laminated Composite Shell type Structures Impacted by a Laser Beam and Explosive Load, $30,000, 3/07-11/07, AFOSR (Batra, 100%)

R. C. Batra, Acquisition of a Parallel Computer, $145,562, 5/04-4/06, ONR (Batra, 100%)

R. C. Batra, Multiscale Modeling Based Design of Tungsten Heavy Alloy Armors & Antiarmors, $90,274, 3/05-3/06, Kennametal Inc. (Batra, 100%)

R. C. Batra, Blast Resistant Marine Sandwich Structures and Nanocomposites, $162,882, 12/1/03-2/28/06, ONR (Batra, 100%)

R. C. Batra, Ballistic Database, Data Analysis, and Interceptor Body Armor Ballistic Performance Modeling, $89,958, 4/1/04-3/31/05, US Army – Natick, MA (Batra, 100%)

R. C. Batra, MURI: Multifunctional Energetic Structural Materials, $275,508, 7/2/02-4/30/05, Subcontract from Georgia Tech (Batra, 100%)

R. C. Batra, Gift, Aliant Techsystem, $9,980, 8/20/02-11/30/04

R. C. Batra, Carbon Nanotube Mechanics, Development of Continuum Models from Molecular Models, $15,000, 8/1/03-8/1/06, VA Space Grant Consortium (Batra, 100%)

A.C. Loos and R. C. Batra, Nonautoclave Processing and Manufacture of Large Reusable Aerospace Structures, $380,000, 7/1/01-6/30/05, NCAM-Louisiana Partnership, (Batra, 50%)

A. C. Loos and R. C. Batra FEM Shrinkage Model Stress Analysis of a Large Thick Composite Cylinder Fabrication with VARTM Resin Systems, $13,469, 12/02-7/03, Naval Surface Warfare Center, (Batra, 50%)

R. C. Batra, Penetration/Fragmentation Analyses, $25,000, 3/1/03-10/31/03, Newport News Shipbuilding & Dry Dock, (Batra, 100%)

R. C. Batra, Localization of Deformation in Heterogeneous Solids Deformed at High Strain Rates, $180,000, 7/01-6/03, ARO (Batra, 100%)

R. C. Batra, Initiation and Propagation of Adiabatic Shear Bands, $21,679, 07/23/01-8/24/01, University of Florida (Batra, 100%)

R. C. Batra and E. G. Henneke, Travel Funds for the Participation of Graduate Students in the 14th USNCTAM, NSF - $9500, ARO - $4000, AFOSR - $8,000, ONR - $9500, 9/15/01-8/31/02 (Batra, 50%)

R. C. Batra, Modeling Material Failure in High Strain-Rate Problems, $60,189, 12/1/00-11/30/01, NSF (Batra, 100%)

F. Chen et al., Center for Excellence in Manufacturing, $4.3M, 7/1/01-6/30/04, Commonwealth of Virginia (Batra, 12%)

R. C. Batra, Adiabatic Shear Band Induced Material Failure Model, $265,801, 2/98-10/02, ONR (Batra, 100%)

R. Kriz, D. Farkas, W. Curtin, R. C. Batra and J. Burton, Computer Simulation of Material Behavior – From Atomistic to the Continuum Level, 6/97-8/01, $220,915, NSF (Batra, 20%)

R. C. Batra, Acquisition of a Computational/Visualization Server, $104,903, 3/99-2/00, ONR (Batra, 100%)

N. Dowling and R. C. Batra, Thermomechanical Analysis of a Rotor and Microstructural Investigations of Candidate Rotor Materials, $63,090, 1/99-1/01, Univ. of Dayton Research Institute (Batra, 50%)

A. C. Loos and R. C. Batra, Resin Film Infusion Process Development, 6/96-10/99, $958,151, Boeing Co., (Batra, 40%) [Batra's participation not listed in the Grant Data Form but listed in Department Overhead Return]

R. C. Batra and D. Inman, Vibration Control of Nonlinear Thermoviscoelastic Plates with Embedded PZT Sensors and Actuators, 10/97-9/00, $219,954, NSF (Batra, 50%)

D. Inman and R. C. Batra, Modeling Damping in High Performance Vehicles, 2/98-1/01, $235,000, ARO (Batra, 50%)

D. Farkas, R. C. Batra, W. Curtin and R. Kriz, Acquisition of a Computation/Visualization Server, $119,911, 5/97-4/98, AFOSR (Batra, 25%)

R. C. Batra, The Interaction between Cracks and Shear Bands, $183, 999, ONR, 9/94-8/97 (Batra, 100%)

R. C. Batra, Analysis of Adiabatic Shear Bands in Thermoviscoplastic Materials under Combined loading, $60,866, ARO, 12/94-12/96 (Batra, 100%)

R. C. Batra, Robust Algorithms in Penetration Mechanics, $255,536, ARO, 12/94-12/97 (Batra, 100%)

R. C. Batra, Fundamental Studies in Adiabatic Shear Bands, $124,019, NSF, 9/94-8/97 (Batra, 100%)

R. C. Batra, Nonlinear and Distributed Control of Smart Structures using Neural Networks, $125,744, 9/94-9/96, Subcontract from University of Missouri-Rolla (ARO), (Batra, 100%)

R. C. Batra, Symposium on Recent Developments in Elasticity, $9,991, 8/95-7/96, ARO (Batra, 100%)

R. C. Batra, Int. Symp. on Recent Advances in Constitutive Equations, $9,499, 6/95-5/96, ARO (Batra, 100%)

(b) *at MUST prior to 1994 (Batra's share = $1.6M)*

V. S. Rao, R. C. Batra, L. Acar, Nonlinear and Distributed Control of Smart Structures using Artificial Neural Networks, $104,000, 1/93-6/94 (Additional internal funds = 30,813) (Batra, 33%)

R. C. Batra, Funds for Research Instrumentation, $75,084, 1/93-8/94, ARO, (Additional internal funds = $18,771) (Batra, 100%)

R. C. Batra, Analysis of Adiabatic Shear Bands in Thermoviscoplastic Materials under Combined Loading, $90,000, 1/92-5/95 (Batra, 100%)

R. C. Batra, Robust Algorithms for Penetration Mechanics Problems, $234,906, 7/92-11/94, ARO (Batra, 100%)

R. C. Batra, Modeling and Characterization of Materials for Dynamic Metal Working Processes, $110,000, 8/91-7/94, NSF (Batra, 100%)

R. C. Batra, Consideration of Microstructural Changes in the Study of Adiabatic Shear Bands, $245,406, 3/91-11/94, ARO (Additional internal funds = $33,400) (Batra, 100%)

R. C. Batra, Adiabatic Shear Band induced Failure in Metals, $30,000, 5/91-11/92, Additional internal funds (Batra, 100%)

R. C. Batra, Partial Support for the 22nd Midwestern Mechanics Conference, $14,459, 7/90-12/91, NSF (Batra, 100%)

R. C. Batra, Partial Support for the 22nd Midwestern Mechanics Conference, $10,000, 6/91-5/92, ARO (Batra, 100%)

R. C. Batra, Adiabatic Shear Bands, $80,000, 8/89-7/91, ARO (Batra, 100%)

R. C. Batra, Adiabatic Shear Bands in Simple and Dipolar Viscoplastic Materials, $ 152,230, 12/87 – 5/90, NSF (Batra, 100%)

R. C. Batra, Studies in Penetration Mechanics, $362,582, 9/85-3/92, ARO (Batra, 100%)

R. C. Batra, Optimum Design of Forging and Extrusion Operations taking into consideration Adiabatic Shear Bands, $12,141, Internal university funds, 12/88 – 6/89 (Batra, 100%)

R. C. Batra, Penetration Mechanics and Adiabatic Shear Bands, $90,000, 8/82-8/83, Ballistic Research Lab, Aberdeen, MD (Batra, 100%)

R. C. Batra and R. Davis, Partial Support for the Society of Engineering Science Meeting, $20,000, 1/82 – 1/83, ARO, AFoSR, NSF, ONR (Batra, 50%)

R. C. Batra, Support for Conference on Mathematical Modeling in Science and Technology, Madras, India, $20,000, 6/88 – 4/89, NSF (Batra, 100%)

CPU Hours (Total estimated value =$1.7M)

500 CPU Hours on IBM 3090 and $5,000 for travel, Estimated value = $405,000, 6/1988 – 5/1989 (Batra, 100%)
49 CPU hours on CRAY-XMP, NSF, Estimate value = $49,000, 1988 – 89 (Batra, 100%)
20 CPU hours on IBM3090 and FPS computer, Cornell Univ. Computer Center, Estimated value = $16,000, 1988-1989 (Batra, 100%)
98 CPU hours on CRAY-XMP, National Center for Supercomputing Applications, Estimated value = $98,000, 1988-89 (Batra, 100%)
300 CPU hours on IBM 3090 machine, Estimated value = $240,000, 1989-90 (Batra, 100%)
100 CPU hours on NSF Supercomputer Center at Cornell Univ., Estimated value = $100,000, 6/1990-6/91 (Batra, 100%)
98 CPU hours on NSF Supercomputer Center in Illinois, Estimated value = $98,000, 3/1991-3/92 (Batra, 100%)
50 CPU hours on NSF Supercomputer Center at Cornell Univ., Estimated value = $50,000, 6/1991-1/92 (Batra, 100%)
500 CPU hours on Ohio Supercomputer Center, Estimated value = $500,000, 5/1992-4/93 (Batra, 100%)
100 CPU hours on NSF Supercomputer Center in Illinois, Estimated value = $100,000, 11/1992-11/93 (Batra, 100%)

PATENTS

Michael Cybulsky, Raymond J. Sinatra, Roy Peter McIntyre, Taylor K. Blair, Gary Pickrell, Romesh Batra, Mark Hudson, Diagnosis of thermal spray gun ignition, **Patent number:** 10241091, Granted on 3/26/2019.

Taylor Blair, Gary Pickrell, Michael Cybulsky, Raymond John Sinatra, Romesh Batra, Analysis of component having engineered internal space for fluid flow, **Patent number:** 10274364, Granted on 4/30/2019.

Taylor Blair, Michael Cybulsky, Gary Pickrell, Benjamin Zimmerman, Romesh Batra, System control based on acoustic Signals, **Patent number**: 10,695,783 Granted on 30 June 2020.

Michael Cybulsky, Raymond Sinatra, Matthew Gold, Taylor Blair, Gary Pickrell, Romesh Batra, 2020.

PUBLICATIONS in PEER-REVIEWED JOURNALS:

Names of doctoral, M.Sc., and undergraduate mentees are, respectively, indicated by an underline, * and **. Students in my ESM6734 (Finite Element Method II) class are marked with ++.

(a) Prior to joining Virginia Tech in 1994

1. R. C. Batra and R. N. Dubey, Impulsive Loading of Circular Plates, *Int. J. Solids and Structures*, **7**, 965-978, 1971 [M.Sc. thesis]

2. R. C. Batra, On Non-Classical Boundary Conditions, *Archive for Rational Mechanics and Analysis*, **48**, 163-191, 1972 [Ph.D. dissertation]

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8. R. C. Batra, Decay of the Kinetic and the Thermal Energy of Compressible Viscous Fluids, *J. de Mecanique*, **14**, 497-503, 1975

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18. R. C. Batra, Decay of the Kinetic and the Thermal Energy of Incompressible Micropolar Fluids, *J. de Mecanique*, **16**, 217-225, 1977

19. R. C. Batra, Cold Sheet Rolling, The Thermoviscoelastic Problem, A Numerical Solution, *Int. J. Numerical Methods Engineering*, **11**, 671-682, 1977

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CLASS-NOTES PUBLISHED:

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Associate Technical Editor - ASME J. Eng'g Mat'l & Tech., (1/96 - 12/00)
Chairman - ASME Elasticity Committee (1995 - 2000)
Member - Editorial Committee, Southeast Congress of Theoretical and Applied Mechanics, 1996
President – Society of Engineering Science, Inc., 1996

Director - Society of Engineering Science, Inc. (1/91 - 12/96)
Director - Midwestern Mechanics Conference Board, 1987-1993; Chairman 1989-91
Reviewer for Applied Mechanics Reviews (1973-78), Shock and Vibration Digest (1972-74)

ORGANIZER AND CONFERENCE CHAIR/CO-CHAIR:

1980 23rd Meeting of the Soc. for Natural Philosophy, Univ. of Missouri-Rolla, Nov. 10-12, 1980
1982 19th Annual Meeting of the Soc. of Engng Sci., Univ. of Missouri-Rolla, Oct. 27-29, 1982
1991 22nd Midwestern Mechs. Conf., Univ. of Missouri-Rolla, Oct. 6-9, 1991
1999 ASME Mechanics & Materials Conf., Virginia Tech, June 27-30, 1999 (> 700 participants; one of the largest participation in the Conf.)
2002 14th U.S. National Congress of Theoretical & Applied Mechs., Virginia Tech, June 23-28, 2002 (1,050 participants; largest attendance in the Congress history)

LISTING IN WHO'S WHO:

Who's Who in America
Who's Who in American Education
Who's Who in Frontiers of Science and Technology
Who's Who in the MidWest
International Directory of Engineering Analysts, Pineridge Press, U.K.
Who's Who in Technology Today
International Men of Achievement
Who's Who in Engineering
American Men and Women in Science

NSF SPONSORED PARTICIPATION IN INT. CONFERENCE:

Soil-Struc. Interaction, Roorkee, India, 1983
Finite Elements in Comp. Mechs., India, 1985
8th Symp. on Earthquake Eng'g, Roorkee, India, 1986
Int. Conf. on Math. Modeling in Sci. & Tech., India, 1988
Int. Cong. on Theor. and Appl. Mechs., Grenoble, France, August, 21-26, 1988

SHORT COURSES TAUGHT:

GIAN (Global Initiative of Academic Networks) course on Nonlinear Continuum Mechanics, IIT-Kharagpur, India, December 2017
https://erp.iitkgp.ac.in/InfoCellDetails/resources/external/cepdata?course_id=CEP/GIC/17-18/ME/2171
GIAN course on Analysis of Nonlinear Problems by the Finite Element Method, Malaviya National Institute of Technology, Jaipur, India, Dec. 2016 (http://mnit.ac.in/news/news.php?news_id=1706)
Nonlinear Solid Mechanics, Nanjing University of Science & Technology, Nanjing, China, August 2016
Finite Element Method, Yangzhou Univ., China, May 2014

Functionally Graded Materials/Structures, Fulbright Specialist, Thapar University, India, December 2013 – January 2014

Engineering and Designing Smart Structures, Virginia Tech, Roanoke, March 1998; Falls Church, Nov. 1998; Munich, Germany, March 1999; Hampton, May 1999; Dayton, Ohio, May 2000; Blacksburg, May 2001; Edinburgh, England, Nov. 2001; Cleveland, Ohio, Dec. 2001, Blacksburg, May 2002; Blacksburg, May 2003; Blacksburg, May 2004. (Organized and taught 25% of the two-day course)

Adiabatic shear bands, Eglin Air Force Base, Florida, August 2001

Localization and Fracture Phenomenon in Inelastic Solids, Int. Center for Mechanical Sciences, Udine, Italy, (Taught 25% of one-week long course coordinated by P. Perzyna), October 1997