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Future Research Directions in Solid Mechanics

Final Report of the American Academy of Mechanics

Submitted to the
National Science Foundation

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January, 2003

Summary

Introduction

The dawning of a new millennium created an incentive for a number of researchers in the field of solid mechanics to gather at a weekend symposium in March 2001 at Northwestern University to exchange views on the future of research in their field. This Workshop was sponsored by the American Academy of Mechanics and the National Science Foundation. In the late 20th century, solid and structural mechanics research addressed engineering and scientific problems of macro-scale mechanics: buildings in earthquakes, aircraft and rockets, and energy and manufacturing technologies. At the beginning of the 21st century the focus has shifted to micro and nano-scale physics and engineering as well as to issues in biomechanics, biomaterials and information science. The theme of the AAM/NSF symposium was the integration of scales between the micro/nano world and the macro-scale that most humans live in. How do we take advantage of technological and scientific advances at the nano-scale and relate this new knowledge, materials and tools to the continuing problems at the macro-scale such as infrastructure, transportation, energy, manufacturing and the new area of homeland defense?

II

Solid Mechanics Research and Homeland Security

This report was scheduled for completion in the Fall of 2001. The events of September 11, 2001 have created new priorities in the Nation. Thus it is natural to ask what role the knowledge base and research talents in the field of solid mechanics might bring to these new priorities. While most of the sub-field summaries below reflect pre 9-11 thinking, the Editor believes that it is incumbent on the mechanics community to reflect on what new thinking can be brought to create a more secure and safe world in the midst of hostile groups and countries.

Within days of September 11, 2001, Professor Z. Bazant of Northwestern University had emailed an analysis of the collapse of the twin towers in New York showing the nature of the progressive failure. His ability to quickly model this terrible event showed both the capabilities of modern structural analysis and the failure of preparedness in the Nation to examine the interaction of aircraft with civilian infrastructure. We in the U.S. research community had spent decades worrying about earthquake dynamics of buildings and nuclear reactors but had never imagined the catastrophe that hit the Pentagon and the World Trade Centers. Yet we had the technical skills to evaluate the dangers inherent in aircraft hitting large buildings. In many ways we have insulated mechanics problems: some of us analyze aircraft and others analyze civil infrastructure or energy structures, but rarely look at cross-disciplinary problems.

The opportunities for new research directions in Homeland Security using the skill base of mechanics and materials science is enormous; such as using new NEMS sensors to detect dangerous objects or designing new explosion resistant netting for aircraft cargo; or using new structural design concepts to resist progressive failures in high rise buildings and creating automatically controlled collision avoidance for aircraft.

In several post 9-11 reports, a rough outline of research needs has begun to emerge. It is evident from reading these reports that a new focus on macro-scale problems will be needed, especially in the area of infrastructure safety. For example in the September 2002 issue of *Mechanical Engineering*, “Designing for Sabotage”, new construction codes for high rise structures will likely call for more structural redundancy to avert progressive failures of the Trade Center example. Also the safety of nuclear facilities and power infrastructure will likely see a renewed emphasis.

In the formal Report of the National Research Council (2002) *Making the Nation Safer: the role of science and technology in countering terrorism,* important chapters impacting mechanics research include,

Chapter 2, Nuclear and Radiological Threats,
Chapter 6, Energy Systems,
Chapter 7, Transportation Systems,
Chapter 8, Cities and Fixed Infrastructure,
Chapter 10, Complex and Interdependent Systems,
Chapter 11, Cross-cutting Challenges and Technologies

It is clear from this list that in contrast to current research Federal priorities in info-nano-bio research, that there will likely be a re-focus on macro-scale research for which mechanics has played a significant role in the past.

In Chapter 2 of the NRC report, their research priorities call for an assessment of nuclear facilities to attacks by airliner and small aircraft. This is clearly an interdisciplinary problem involving both aerospace mechanics and infrastructure structural mechanics.

In Chapter 6 of the NRC report, R&D priorities call for investigation of new material coatings for structures to resist fire and blast shock. It also calls for new simulation models for failure cascade phenomena. Also needed are new self-monitoring sensors to detect the onset of failure in oil and gas industries.

In Chapter 7 of the NRC report, recommendations are made for new designs for tamper-proof shipping containers with electromechanical seals as well as new robotic machines to explore dangerous environments. New research is called for in bio-chemical ventilation filters for subway and tunnel systems. Similar priorities are called for in Chapter 8 related to Cities and Fixed Infrastructure. New blast and fire resistant structures, studies of explosions in tunnels, bio-chemical filters for HVAC systems, new concepts on structural connections between elements to avoid progressive failures of the Twin Towers type are recommended for future research and development.

From this list, one can see a potential research opportunity in bridging the macro and micro scales especially in the areas of new sensors, new bio-chemical filters, and fire resistant structural coating. The need to address the multi-scale problem in mechanics came up at the Workshop again and again.

Summary of Research Opportunities and Priorities

The Millenium marker produced a number of other studies in reviewing the research progress in the field of mechanics including two reports sponsored by the U.S. National Committee on Theoretical and Applied Mechanics on Solid Mechanics (Dvorak, 2000) and Computational Mechanics (Oden, 2000) as listed below in the References to this Summary. The American Academy of Mechanics did not want to duplicate these excellent reports and decided to bring to the Workshop a number of younger researchers in Mechanics. Of the approximately forty participants, about 50% were under the age of 50. Each of the participants wrote a short Pre-Workshop vision statement. These reports were printed and distributed before the Workshop. These reports are included as Appendix 3 of this report. While the majority of the participants were from academia, the organizers were able to bring to the Workshop researchers from a number of industrial and governmental research centers including, General Electric Corporate Research, Rockwell Science Center, National Institute for Standards on Technology, Oak Ridge National Laboratory and Sandia National Laboratory.

The Workshop goals were to identify research priorities that the community of engineers and scholars think will yield the highest intellectual and technical payoff in the next 5-10 years, and to address educational issues related to teaching of solid mechanics. Two overall themes in the discussion were the macro-micro scale issue and the behavior of complex systems.

The Macro-Micro Scale Problem

Solid mechanics has always played an important role in physics and engineering at both micro and macro scales from earthquakes to disc drives, from jet engines to heart valves. However recent directions have carried solid mechanics research into the nanometer and cellular biology scales in ways that compliment both materials science and biology approaches. It is now recognized that fundamental problems of friction, fracture, and mechanical failure at the macro scale remain unsolved from a basic physics point of view. New approaches by researchers in solid mechanics are aimed at bridging the knowledge gap between the molecular and the macro. This knowledge it is hoped will lead not only to new understanding of failure and material behavior but also new technologies in areas such as smart materials, MEMS and bio-technical devices.

Complex Systems

A related opportunity exists in the dynamics of complex solids, structures and machines. In spite of the tremendous acceleration of information technology, the dynamic simulation of complex systems with 1000's of parts and subsystems represents a major challenge. Complex nonlinear systems often tend to have emergent global behavior that cannot be predicted from a reductionist approach by a study of subsystem components. Again this is a multiscale problem across spatial, topological and temporal scales.

Energy Technology

Finally there is the recurring challenge of energy technology and the environment in which materials science and mechanics have played crucial roles in the past. Today there is a new challenge for the mechanics community to seek opportunities to contribute to energy science, which the recent progress in information technology as well as societal quality of life depends.

Education in Mechanics

Many Workshop participants recognize that new directions in solid mechanics research will require new educational curricula at both the undergraduate as well as graduate levels in areas such as quantum mechanics, electromagnetics, chemistry and biology. Also the emergence of new designed materials will require students to be taught new mathematical tools such as optimization and statistical methods as well as the traditional differential equations base. The Workshop did not address computational mechanics, which was recently reported on in a US TAM report. It was recognized that progress in solid mechanics will depend on both new software and computer hardware. However the community believes that whatever the advances in information technology, progress in solid mechanics will continue to depend on good models, fundamental physics and science.

Unranked Overall Priorities in Solid Mechanics Research

1**. *Modeling multi-scale problems***:
    i) bridging the micro-nano-molecular scale,
    ii) macro-scale dynamics of complex machines and systems.

2. ***New experimental methods***:
    - i) micro-nano-atomic scales,
    - ii) coupling between new physical phenomena and model simulations.

3. ***Micro and Nano-mechanics***:
    - i) constitutive models of failure initiation and evolution,
    - ii) bio-cell mechanics,
    - iii) force measurements in the nano-fN regime

4. ***Tribology***, ***Contact mechanics***:
    - i) the search for a grand theory of friction and adhesion,
    - ii) molecular-atomic based models,
    - iii) extension of micro-scale models to macro applications.

5. ***Smart, active, self diagnosis and self healing materials***:
    - i) MEMS/NEMS and biomaterials,
    - ii) fundamental models,
    - iii) increased actuator capability,
    - iv) application to large scale devices and systems.

6. ***Nucleation of cracks and other defects***:
    - i) electronic materials,
    - ii) nanomaterials.

7. ***Optimization methods in solid mechanics***:
    - i) synthesis of materials by design,
    - ii) electronic materials,
    - iii) optimum design of biomaterials.

8. ***Non classical materials***:
    - i) foams, granular materials, nanocarbon tubes, smart materials.

9. ***Energy related solid mechanics***:
    - i) high temperature materials, coatings,
    - ii) fuel cells.

10. ***Advanced material processing***:
    - i) high-speed machining,
    - ii) electronic and nano devices, bio devices, biomaterials.

11. ***Education in mechanics***:
    - i) need for multidisciplinary education between solid mechanics, physics, chemistry, biology,
    - ii) new mathematical skills in statistical mechanics, and optimization methodology.

12. ***Problems related to Homeland Security*** (Post Workshop; Added by the Editor)
    - i) Ability of infrastructure to withstand destructive attacks.

ii) new safety technology for civilian aircraft.
iii) new sensors, robotics,
iv) new coatings for fire resistant structures,
v) new bio-chemical filters.

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Dvorak, G. (Editor) “Research Trends in Solid Mechanics” sponsored by the United States Committee in Theoretical and Applied Mechanics Published in *International J. of Solids and Structure* 2000.

J. Tinsley Oden (Editor) “Research Directions in Computational Mechanics” sponsored by the United States Committee in Theoretical and Applied Mechanics, Fall, 2000.

“Designing for Sabatage” *Mechanical Engineering*, September 2002.

National Research Council “Making the Nation Safer. The role of Science and Technology in Countering Terrorism”, 2002.

Theme Area Groups

Workshop participants were grouped into ten **research focus groups**. Each group prepared a list of bullets (see Appendix I) from which a summary report was written after the Workshop. In a couple of cases a group report did not emerge in which case several individual reports are listed below.

1. Active Materials (D.M. Barnett, R. James, N. Sottos, A. Masud).
2. Mechanics of Biomaterials, Biomechanics (G. Bao, S. Cowin, K.Chong, K. Ravi Chandar).
3. Designed Materials, Composites (G. Dvorak, M. Pelegri, P. Ponte-Castaneda S. Torquato).
4. Foams, Granular Materials and Ceramics (R.S. Ruoff, A.M. Kraynik, J.Jenkins).
5. Fracture and Fatigue (B.N. Cox, K. Ravi-Chandar, H.D. Espinosa, A. Zehnder, Z. Suo).
6. Tribology and Contact Mechanics (L. Keer, J. Streator, R.W. Carpick).
7. Damage Mechanics, Plasticity (D. Krajcinovic, K. Garakipati).
8. Dynamic of Solids and Structures (J. Achenbach, E.H. Dowell, G. Ravichandran, S. Shaw, S. Simunovic).
9. Experimental Mechanics (I.M. Daniel, K.S. Kim, W. Knauss, L. Virgin).
10. Mechanics of Materials Processing (M. Davies, M.S. Fofana, J.A. Ruud).
11. Computational Mechanics (T. Belytschko)

Group Reports

AAM/NSF Workshop on Future Directions in Solid Mechanics

Group Area Reports

Active Materials

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Introduction

Active materials have the ability for controlled adaptation of their physical properties or dimensions to stimuli that can be mechanical, thermal, optical, chemical, electrical or magnetic in nature. Much of the early mechanics research on active material systems has focused on large-scale actuation and control of aerospace structures by bonding piezoelectric patches (dimensions on the order of hundreds of mm in length) to the substructure or embedding long shape memory alloy wires (diameter on the order of hundreds of microns) in laminated composite panels. Although the use of these larger scale, bulk forms of active materials have proven effective for structural vibration control, wide-spread application is limited by the significant energy requirements and low mechanical reliability of these materials. The work output per unit volume (per cycle) for various actuator systems is summarized in Table 1. A major challenge for advancing applications of active materials is the development of improved materials with higher energy densities, larger actuation strains and higher reliability. Simultaneously, the most promising applications require miniaturization of active material systems. The reduction in size has tremendous technological benefits as these materials can be used for improved micro-actuators and sensors in micro electromechanical systems (MEMS) with application to biological/medical devices, automobiles, robots and a variety of aerospace, civil and mechanical engineering structures.

The concept of miniaturized active material systems is somewhat analogous to the use of radioactive tracers in medical diagnostics. Whereas the tracers are used to pinpoint trouble spots within the human body, embedded active materials are used to locate and respond to (possibly even heal; White *et al.* 20001) defects in structural materials. Just as the miniaturization of electronic devices such as microprocessors and memories has led to a decrease in their price and improvement in performance, the development of micro-actuators and sensors should lead to dramatic increases in capabilities of these materials (Trolier-McKinstry and Newnham, 1993). Active materials in the form of thin films, small diameter fibers, particulates, and gels are all candidates for miniaturized smart systems and often have higher energy densities and strain capabilities than their bulk counterparts.

Small scale active material systems present an immediate challenge for solid mechanics research. These materials will exhibit strongly coupled responses between mechanical stress, temperature, electric and/or magnetic fields, which may depend on the geometric form and size scale being used. It is critical to determine the limiting material length scales for active material behavior and define the fundamental material properties necessary for high performance - *i.e.* what are the absolute limits for miniaturization of active materials and what are the important properties to control/optimize on smaller scales? New multiscale methods of analysis along with

Table 1. Power output of some common active materials, taken from P. Krulevitch et al. (1996).

Actuator Type	W/v (J/m^3)	Equation	Comments
1. Ni-Ti SMA	2.5×10^7	$\sigma \cdot \varepsilon$	max. one-time output: $\sigma = 500$ MPa, ε=5%
	6.0×10^6	$\sigma \cdot \varepsilon$	thousands of cycles: $\sigma = 300$MPa, $\varepsilon = 2\%$
2. Solid- Liquid Phase Change	4.7×10^6	$\frac{1}{3}\left(\frac{\Delta v}{v}\right)^2 k$	k = bulk modulus = 2.2 GPa (H_2O) 8% volume change (acetamide)
3. Thermo-pneumatic	1.2×10^6	$\frac{F \cdot \delta}{v}$	measured values: $F = 20$ N, $\delta = 50\mu$m, $v = 4$ mm $\times$ 4 mm $\times$ 50μm^3
4. Thermal Expansion	4.6×10^5	$\frac{1}{2}\frac{(E_s + E_f)}{2}(\Delta\alpha \cdot \Delta T)^2$	ideal, nickel on silicon, s = substrate, f = film, δT= 200°C
5. Electro-magnetic	4.0×10^5	$\frac{F \cdot \delta}{v} \quad F = \frac{-M_s^2 \cdot A}{2\mu}$	ideal, variable reluctance: v = total gap volume, $M_s = 1V$-sec/m^2
	2.8×10^4	$\frac{F \cdot \delta}{v}$	measured values, variable reluctance: F = 0.28mN, $\delta = 250\mu$m, $v = 100 \times 100 \times 250\mu$m^3
	1.6×10^3	$\frac{T}{v}$	measured values, external field: Torque = 0.185 mN-m, $v = 400 \times 40 \times 7\mu$m^3
6. Electrostatic	1.8×10^5	$\frac{F \cdot \delta}{A \cdot \mathrm{gap}} \quad F = \frac{\varepsilon V^2 A}{2\delta^2}$	ideal: V = 100 volts, δ =gap= 0.5μm
	3.4×10^3	$\frac{F \cdot \delta}{v}$	measured values, comb drive: $F = 0.2$ mN (60 volts), $v = 2 \times 20 \times 3000\mu$m^3 (total gap), $\delta = 2\mu$m
	7.0×10^2	$\frac{F \cdot \delta}{v}$	measured values, integrated force array: v=device volume, 120 volts
7. Piezoelectric	1.2×10^5	$\frac{1}{2}(d_{33}E)^2 E_f$	calculated, PZT: E_f = 60 GPa (bulk), d_{33} = 500 (bulk), E = 40 kv/cm
	1.8×10^2	$\frac{1}{2}(d_{33}E)^2 E_f$	calculated, ZnO: E_f = 160 GPa (bulk), d_{33} = 12 (bulk), E = 40 kv/cm
8. Muscle	1.8×10^4	$\frac{1}{2}(\sigma \cdot \varepsilon)$	measured values: $\sigma = 350$kPa, $\varepsilon = 10\%$
9. Microbubble	3.4×10^2	$\frac{F \cdot \delta}{v_b}$	measured values: bubble diam.=71μm, $F = 0.9\mu$N, $\delta = 71\mu$m

new, more powerful experimental techniques for small scale property characterization must be developed to answer these key questions. Mechanics will also play a critical role in the development of new active materials and processing methods. Because of the inherent interdisciplinary nature of this research area, collaborative/team efforts with researchers in chemistry, biology, solid state physics and materials science are essential and may require a significant change in the way solid mechanics students are educated.

Promising Research Directions

The most significant opportunities in the area of active materials are being driven by miniaturization. Key fundamental scientific issues and promising technological issues related to active material miniaturization are listed below.

Fundamental Scientific Issues

- *Multiscale Methods for Active Materials*

As the physical dimensions of an active material become smaller and smaller, surfaces and interfaces will dominate the behavior and continuum methods may no longer be applicable. Discrete (lattice or atomic) computations may be necessary for *ab initio* calculations of physical and mechanical properties, energy and kinetics (moving phase boundaries) of these materials. Since the critical length scale for active materials is the microstructural scale (microns), development of multiscale methods to pass effectively from a discrete atomic scale to continuum scale is essential.

- *Small Scale Physical and Mechanical Property Characterization*

As active materials are developed on smaller scales, the need to characterize physical and mechanical properties is critical. In general, there is a lack of adequate experimental techniques to characterize mechanical behavior and coupled field response at small scales. New approaches are needed that recognize interfacial effects and surface energies and that can provide experimental data to complement multiscale modeling efforts.

- *New Materials Development*

The development of new and better active material systems for miniaturization is a major challenge for the future. Materials with big first order phase transitions (i.e. ferromagnetic shape memory or relaxor ferroelectrics), novel methods of energy conversion (i.e. nano-photosynthesis), interesting electromagnetic or optical properties are the most promising. These new materials may include thin film forms of hard, crystalline materials or soft gels and polymers.

- *Materials Processing*

Small changes in material composition or processing conditions can significantly change the performance of these materials. Future developments in self-assembly, patterning by traditional lithographic processes and new soft lithographic and microcontact printing techniques may provide promising technologies to process active materials with complex microstructures as well as the ability to integrate multifunctionality (e.g., electrical, magnetic, mechanical, optical, etc.) in a single device.

Technological Issues

- *Smart Biomedical Devices*

Active materials have the potential to make a huge impact on the development of *smart* biomedical devices. A current example is the four-year-old, $1 billion business of shape memory stents that are used to prop open clogged or collapsed blood vessels after angioplasty. Continued development of biocompatible active materials may enable to devices that can deliver drugs, perform biopsies and monitor biological function all while be controlled remotely from outside body.

- *Microfluidics*

Active materials are excellent candidates for pumps and valves to regulate flow in microfluidic devices. Large work output is critical at small scales where surface tension effects dominate. The work output delivered by shape memory alloys is an order of magnitude larger than that of electrostatic actuators currently used in MEMS devices.

Hence, materials with large first order phase transitions (discussed above) are particularly promising for these applications.

- *Integration of Microelectronics and Mechanics*

  Advances in self-assembly, patterning and multilayer processing techniques (discussed above) will enable integration of active materials into microsystems on chip. This integration will lead to the development of future devices where materials can sense, move and actuate on a chip.

- *Integration in Active Composites*

  Active materials can be embedded in a host material to form a composite with specific functionality that can be tailored for desired effective properties, field concentration or symmetry. For example, the development of electrically active ceramic-polymer composites has led to significant improvement in transducer material properties over the past decade. Exciting possibilities for the future include use of active material systems to incorporate damage detection, shape control and even healing capabilities in a composite.

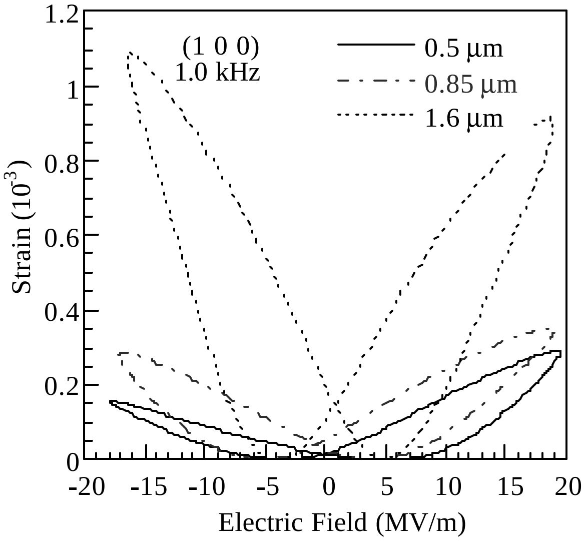

Fig. 2: Interferometrically measured field induced strains for PZT (52/48) ferroelectric thin films (Lian and Sottos, 2000).

Discussion

Miniaturization of active material systems is critical for developing the next generation of technological applications. But as the material length scale decreases, the fundamental material properties that define the performance of an active material are going to change. How the properties change and the absolute limits for miniaturization of active materials are the key unknowns. Recent experiments on ferroelectric thins films have revealed significant changes in the properties and performance piezoelectric coefficients, field-induced strains and dielectric constants with changes in film thickness and preferred orientation of the films (Lian and Sottos, 2000). Fig. 2 shows the dramatic increase in field-induced strain with increasing film thickness for a film with (100) preferred orientation. The linear piezoelectric constants and dielectric constants also increased with film thickness. In addition, films with (100) preferred orientation were found to have higher piezoelectric constants and dissipation loss factors than films with (111) preferred orientation. Lian and Sottos (2000), as have others, hypothesized that the residual stress state in the film is a key factor leading to the size dependent behavior observed experimentally.

Martensitic transformations in shape memory materials may also be affected by miniaturization. Turnbull (1950) showed that the phase transformation is suppressed at small scales. To change the phase of the material from phase A to phase B, an interface has to move through it. If the material length scale is sufficiently small, the possible lowering of free energy due to the presence of B may be overcompensated by the interfacial energy of the A/B interface, hindering the transformation. This reasoning may be flawed however. The nanoscale organism Bacteriophage T-4 has a transformation of its tail that is convincingly martensitic (). It uses the transformation to penetrate the cell wall of the bacterium that is invades. New methods of analysis combined with careful experimental characterization are critical to understanding the complex coupled behavior of active materials at the nanoscale and advancing the development of miniaturized systems.

At some critical size scale, continuum methods will break down and discrete atomic level computations may be necessary to fully understand active material behavior. The question of how to define configurational or Eshelby-like forces in a discrete lattice will need to be addressed. Density functional theory (DFT) is already being used to calculate the energy and forces in active material systems such as NiTi and Pb(Zr-Ti)O_3, but analysis of 10 nm x 10mm x 10nm deformed cube using current DFT methods (N^2) requires 2million years. Development of multiscale methods of analysis that can link behavior on the atomic scale to the microstructural scale to the continuum scale is essential.

New experimental techniques are also needed to characterize mechanical behavior and coupled field response at small scales. Current methods include atomic force microscopy (AFM), transmission electron microscopy (TEM) with digital image correlation and nano-indentation. While these techniques are powerful for probing and imaging materials at a small scale, it is difficult to apply them to accurately and reliably determine mechanical properties such as modulus or fracture toughness, especially for very thin film films (~50 nm) on a substrate. Determining coupled field response is equally as difficult. Small scale testing combined with interferometric measurements is promising but the limitations due to gripping and compliance need to be addressed. Other promising techniques include GHz laser-ultrasonics and Brillouin light scattering but much more research is necessary to apply them to active material characterization.

Another important problem in the development of active materials on the micro or nanoscale is the lack of understanding of the complex structure-property-processing relationships for these materials. Small changes in material composition or processing conditions can significantly change the performance of these materials. Significant residual stresses are also developed during the processing of active materials in thin film form. The residual stresses depend significantly on the intrinsic processing history and the extrinsic mismatch in properties between the film and the substrate. Advances in modeling methods and experimental characterization described above need to be carried out in collaboration with new materials development and new processing methods such as self –assembly and patterning to achieve optimal microstructures.

Perhaps one of the most far-reaching possibilities is the development of materials systems that integrate multifunctionality (e.g., electrical, magnetic, mechanical, optical, etc.) in a single chip-scale device or composite. Recent advances in non-lithographic patterning processes and robotically controlled deposition of electroceramic materials provide enabling technologies to process materials with complex microstructures consisting of two or more functional materials.

The ability to integrate active materials and tailor functionality to sense, actuate, regulate or regenerate leads to new paradigm in materials design, that of autonomy – the ability to achieve adaptation and response in an independent and autonomic fashion. A vision for the future is to combine different functionalities to synthetically reproduce autonomic biological functions in complex, integrated material systems.

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XIV

Biomechanics and Biomaterials

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Introduction

With recent advances in cell and molecular biology, genetics, biotechnology and medicine, biomechanics and biomaterials research has entered a new era in which cellular functions and molecular mechanisms have become a new focus. The behavior of cells and tissues as complex biological systems is a result of integrated and regulated interactions among many components such as cell cytoskeleton, extracellular matrix (ECM), signal transduction pathways, intracellular secretion/transport, and gene expression. Mechanical forces and deformations may play an important role in all these aspects, and in regulating cell behavior and function. Further, mechanical analyses can provide useful tools for modeling and quantitative prediction. Continuum mechanics has been successful in modeling whole-cell and tissue deformation in response to applied forces. However, to understand mechanics issues at the cellular level, it may no longer be adequate to simply lump all specific force-bearing, force-generating, and force-sensing elements into a structureless continuum - more subcellular and molecular structures and mechanisms need to be studied. For example, a major issue in biomechanics is how cells sense mechanical forces or deformations and convert them into biochemical and biological responses. As possible mechanisms of such mechanochemical coupling, mechanical forces may regulate cell behavior and function by deforming DNA and proteins, influencing the transport of ions and other molecules, and altering receptor-ligand binding kinetic rates and specificity. In all of these mechanisms, the deformation of individual biomolecules under force may play a central role.

As a basic discipline in engineering and science, mechanics has made tremendous progress over the last century. There is little doubt that the new century is a biotech century and mechanics can play an important role in advancing biology and medicine. In particular, the impact of mechanics issues, from organ and tissue levels to cellular and molecular levels, has been realized by more and more clinicians and biologists alike, especially in orthopedics, cardiovascular, space and reparative medicine. Mechanics analysis has become indispensable in the design and engineering of many medical devices, such as those for bone fixation, cartilage and total hip replacement, artificial organs, to name only a few. Cell mechanics, addressing issues in cell locomotion, cell adhesion, cell spreading, cell-ECM interactions, and the dynamics of cell cytoskeleton, is important to wound healing, immunology, cell and tissue engineering, and cancer studies. Mechanics issues in proteomics and biotechnology have also begun to attract attention, including those in protein and DNA conformational dynamics, diffusion, reaction and secretion of biomolecules, and structure-function relationship of molecular motors. In what follows, we present our view of the future research directions in biomechanics and biomaterials over the first few decades in the 21^{st} century, aiming to stimulating a broader interest in the solid mechanics community

Future Research Directions

- *Cell and Tissue Engineering*

  Cell adhesion, cell-scaffolding interactions; the role of forces in tissue growth and remodeling; mechanical strength of scaffolds and microcapsules; diffusion/transport of nutrients and metabolites

- *Molecular Biomechanics and Bioengineering*

  Deformation and dynamics of DNA and protein molecules; mechnochemical coupling in molecular motors and machines; diffusion-reaction and mixing in microfluidics, DNA chips and protein chips; the mechanics of nano-structured biofilters and membranes

- *BioMEMS and BioNEMS devices*

  BioMEMS for mechanical testing of cells; interfacing living cells with MEMS/NEMS; active devices driven by cells/biological motors; deformation-based biosensors

- *Microgravity and Space Medicine*

  The role of gravity in molecular, cellular and developmental biology and human health; countermeasures in space medicine

- *Biomaterials and Biomedical Devices*

  Surfaces modified by extracellular matrices and other biomolecules; self-assembly of biomolecules; biocompatibility, stability and durability of biomedical devices; design of biomedical devices; biocomposites

- *Biomechanics Issues in Human Aging, Health and Sports*

  Biomechanics issues in elderly people (e.g., bone fracture), occupational diseases (back-pain, etc), traumatic body injury, structure and motion of human body as a dynamic system, biomechanics of surgery and wound healing

- *Biomedical Modeling and Computing*

  Integration of different biological aspects; computational biomechanics

Discussion

From the basic science point of view, a central issue in biomechanics and biomaterials is how mechanical forces regulate cell behavior and function. As the basic unit of life, living cells are complex biological systems. To perform their specialized functions, cells must express genetic information; synthesize, sort, store and transport biomolecules; convert different forms of energy; transduce signals; maintain internal structures; and respond to external environments (Alberts et al, 1994). Many of these processes involve mechanical issues. For example, recent studies have confirmed that mechanical forces can affect cell growth, differentiation, locomotion, adhesion, signal transduction, and gene expression (Zhu at el, 2000). Yet little is known about how cells sense the mechanical forces and deformations, and convert these mechanical signals into biological or biochemical responses. There is an increasing need to understand the cellular and molecular mechanisms by which cells generate, detect, and respond to mechanical forces.

Key Unsolved Problems There are a number of unsolved problems in cellular and molecular biomechanics, including: (1) force distribution, transfer and balance in individual cells and cell/ECM systems under physiological conditions; (2) forces and moments applied to biomolecules in living cells; (3) deformation of DNA, RNA and protein molecules under mechanical forces; (4) mechanisms and dynamics of molecular motors; (5) mechanics of protein/protein and protein/DNA interactions; (6) mechanisms of how forces regulate cell adhesion, ion transport and vesicle trafficking. In solving these problems, it is critical to establish the connection between mechanics and biochemistry. In particular, we need to understand the effects of mechanical force and motion on conformational dynamics, binding/reaction and transport of biomolecules, and the effect of solvent chemistry on mechanical deformation of proteins and DNA.

Major Challenges To further develop biomechanics, we face some major challenges in both experimental and theoretical studies. These include: (1) small sizes of protein molecules (1-100 nm) and small forces involved (0.1-200 pN); (2) lack of theoretical models for protein folding/unfolding and protein/protein, protein/DNA interactions; (3) the need to integrate solid/fluid mechanics, thermodynamics, statistical mechanics with biochemistry and molecular biology; (4) molecular dynamics simulations are not only time-consuming but also often unreliable; (5) lack of structural information and good imaging systems to visualize and quantify deformation of proteins (Subbiah, 1996); (6) better experimental and theoretical approaches to quantify the mechanical properties of cells and tissues. These challenges pose new mechanics issues to people in solid mechanics.

- *Cell and Tissue Engineering*

In developing engineered tissues, many biomechanics and biomaterial issues need to be addressed (Cowin, 2000). Examples include cell adhesion, cell-scaffolding and cell-cell interactions, and the mechanical environment necessary for the growth, strengthening, viability, and immuno-response of the tissue (blood vessel, bone, cartilage, etc). In particular, we need to understand and quantify the effect of forces on cell-ECM and cell-cell interactions through integrin molecules, cell cytoskeletal dynamics, and mechanochemical transduction. We also need to quantify the mechanical strength of scaffolds and microcapsules.

- *Molecular Biomechanics*

As possible mechanisms of mechanochemical coupling in living cells, mechanical forces may regulate cell behaviors and functions by deforming DNA and proteins. Mechanical forces, including viscous drag force, are also important to the functions of molecular motors. Molecular biomechanical is very important to a wide range of problems in life sciences, biotechnology and medicine over the next few decades (Bustamante et al, 2000). However, we still do not know the dependence of protein deformation on their specific structures, solvent environment, and applied forces. We still do not know how such deformations alter biochemical processes such as receptor-ligand binding, cell-cell and cell-ECM adhesion, cytoskeletal dynamics, and gene regulation and expression. We are facing great challenges, both theoretically and experimentally, in the studies of biomolecular deformation.

- *BioMEMS*

As an innovative system, BioMEMS has enormous potential in revolutionizing the way we solve biomedical problems. For example, it can be used for studying the force generation, signal transduction, secretion control and cytoskeletal dynamics of individual living cells; it can be used to sort, manipulate and control cells. BioMEMS devices can also be made to mimic the function of, or to be powered by, molecular motors. It is also possible to develop BioMEMS devices for the diagnosis, prognosis, and treatment of human diseases and viral infection. It is even possible to develop BioMEMS and BioNEMS (nanoelectromechanical systems) devices to mimic the behavior and function of specialized cells. Needless to say, mechanics is indispensable to the development of BioMEMS.

- *Proteomics*

With the successful completion of the Human Genome Project, a new field of proteomics, i.e., the systematic study of protein structure and function has emerged. Although DNA microarrays are now being widely used in quantifying up- or down-regulations of genes, it is necessary to develop more quantitative DNA chips. It is even more important to develop protein chips for proteomic studies. Since proteins cannot be amplified, mechanics issues such as molecular deformation, transport, diffusion and binding between antibodies and antigens will be very crucial to the design of protein chips. The mechanics of protein deformation under force is certainly part of proteomic studies, for it provides a dynamic picture of the proteins, and links the protein dynamics to function.

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XVIII

Designed Materials, Composites

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Introduction

By definition, composites and designed materials are heterogeneous systems consisting of two or more constituents, or phases, with given distribution, or microstructure. Traditionally, the microstructure was assumed to be given, although perhaps not precisely (e.g., random), and the goal was to determine the effective, overall, or macroscopic response of the composite material system. Increasingly, the goal has become not only to be able to predict the response of the system, as a function of their constituents and microstructure, but also to design or optimize the microstructure to satisfy appropriate design objectives/constraints. There are, of course, many different issues and problems of interest in the context of such materials, but perhaps the most central one is the above-described problem of assessing the macroscopic behavior, or homogenization. However, it is essential to be able to go beyond the average properties of the system. For example, failure of composite usually takes place through localized modes of deformation, far away from the domain of validity of the standard homogenization theories. In this connection, it is important to emphasize that, in a broader interpretation, homogenization can give useful, additional information, about the effective properties of the material.

Another very important issue is the study of heterogeneous structures in the micro- and nanoscale, which has been proved to be by far more complex than the reciprocal one of metallic materials. For example, nanotechnology has resulted in an increased understanding of solid-liquid interactions such as surface wetting. This knowledge has important implications for preventing wear on engines, paintings and buildings, for medical products such as contact lenses, surgical tools and prosthetics. Our ability to understand and control surface wetting has dramatically improved, since our ability to observe and fabricate nanoscale surface topographies has been developed. Yet, research tools need to be developed in order to enable the performance of quantitative studies that will elucidate the governing phenomena that control the behavior and performance of these structures. The current state of affairs in the field of heterogeneous materials at the nanoscale is mostly qualitative and empirical.

Furthermore, our ability to use synthetic means to fabricate materials, devices and systems on the microscale is currently far superior to our ability to do so on the nanoscale. The field known as MEMS is well established due to the numerous commercial applications, for instance accelerometers for airbag deployment in automobiles, ink jet printer heads, color projection displays and scanning probe microscopy. Furthermore, the silicon semiconductor industry has provided numerous methods for fabricating microscale electronic devices. With a little ingenuity, these same methods can be used to convert electrical energy into mechanical energy, and vice-versa. Fields, emerging from the successful MEMS research, in which nano and molecular scale manipulation of matter is receiving abundant attention is medicine (Fig. 1).

Since all living organisms are composed of molecules, molecular biology has become the primary focus of biotechnology. Molecular medicine, bioinformatics and biomolecular nanotechnology are rapidly increasing our ability to heal and stay healthy. However, although we have all these wonderful applications, there is a dare need for basic research to be performed in this area. One that will lead in enhanced understanding of the underlying physical phenomena and, eventually, in more sophisticated applications.

All of the above results would not have been realized if tenuous research efforts were not undertaken. The fruits of such efforts have enabled us to resolve key research issues such as:

- Fracture and failure mechanics of nominally homogeneous materials.
- Relationships between the physical properties of heterogeneous materials to the microstructure, including linear and nonlinear properties.
- Development of efficient algorithms as well as the increased speed of computers.

The resolution of the aforementioned fundamental issues has enabled us to further the research horizons to new and exiting areas. To this extent, there are eight topics described in the section below, which are the most promising areas in the study and advancement of heterogeneous materials and structures.

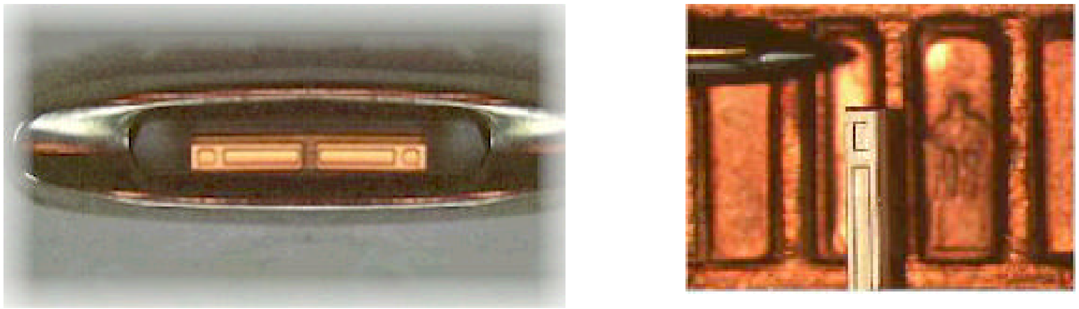
(a) (b)

Figure 1: Medical Pressure sensor just 350 microns (10^{-6} m) wide (a) in the eye of a needle, (b) detail.

Promising Research Directions

- *Three-dimensional imaging of heterogeneous materials.*

  Most of the existing imaging techniques are not up to the task of efficiently and effectively capturing the deformation and stress fields of heterogeneous materials and structures. That is, most of these techniques were developed for metallic materials and cannot portray the idiosyncrasies of composite materials and structures.

- *Transforming diverse physical phenomena into common interaction space.*

  Many problems in heterogeneous media involve interaction of several diverse physical processes. Interactions and couplings in such systems are often very complex within each length scale, and taking place at several length scales, hence their understanding could be advanced by transforming their effects into equivalents in a common interaction space. Further research in this area, with focus on nanoscale and hierarchical interactions should open new avenues of understanding of interactive and coupled phenomena.

- *Optimization for material microstructure design – inverse problems, multifunctionality.*

  Complex, microstructures determine the fundamental properties of multifunctional materials. Consider for example, active materials, i.e., shape memory alloys, whose behavior depends on a phase-separation kinetics and exchange of stability among competing microstructures. In order to advance multifunctionality of such materials, optimization schemes for macroscopic material properties by promoting certain microstructures, is required.

- *Damage retardation and control by residual stress distributions.*

  The currently available manufacturing processes and operational cycles of engineering components lead to the accumulation of residual stresses in the structure. S. P. Timoshenko drilled a hole in metallic plate in order to achieve stress relief. To this extent, new methodologies should be devised, and new models developed to utilize the residual stress distributions for damage control and retardation in composite materials and structures.

- *Wedding statistical mechanics with continuum theories.*

  For the efficient use of nanomaterials in structures, the links between statistical inhomogeneity and strength of micro and nanostructures, field fluctuations, non local effects, and quantum mechanics on hand, and, macroscopic ëreal worldí properties of bulk matter such as pressure, heat capacity, magnetic susceptibility etc. on the other, should be studied.

- *Microstructure exploration and control (active materials, processing).*

  In the field of composites, i.e., heterogeneous materials, most of the constitutive equations are “borrowed” from the ones developed for homogeneous metallic materials. Nevertheless, not all the assumptions made about metallic materials hold in the case of composites, i.e., piezoelectric materials, materials with negative Poisson’s ratio. As such, there is a dire need in the engineering community for better understanding the governing equations of heterogeneous materials and structures in order to fully utilize their design and performance capabilities.
- *Analyze biological materials as heterogeneous materials with structural hierarchy and scale interactions.*

  Materials used in biomedical and bioengineering applications are constantly interacting with organic and inorganic materials and structures (Fig. 2). Currently medical doctors and fellow engineers are utilizing these materials on a need to know, qualitative basis. However, the full potential of biological materials will be unveiled once quantitative constitutive and scale laws are developed. These laws are the basis on which exciting developments in (i) processing, (ii) characterization in terms of engineering and surface properties, (iii) assessment of cell and tissue interactions with the materials, and (iv) methods for assessing material performance and biocompatibility following in vivo use, are expected.

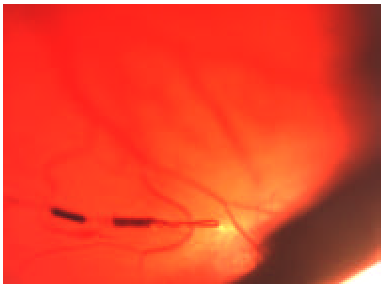

Figure 2: An implantable biosensor will provide pain-free, reliable and continuous monitoring of blood sugar levels in diabetics.

- *Educational training: condensed mater physics, biology, quantum mechanics, state-of-the-art experimental techniques.*

  Student should acquire training in areas in which they are expected to perform. It is only natural for example, to have students trained in modern experimental techniques, as well as in quantum physics, if we expect them to carry out measurements in the nano- and atomic scales. The traditional curriculum in most schools does mechanical engineering and applied sciences schools does not cover these courses and is up to the advisors to transfer their expertise to their students. Nevertheless, a more universal program should be devised and adopted by the engineering schools.

Discussion

Why is nanotechnology important? Well imagine:

- molecular-sized machines that float in your bloodstream, carving away arterial plaque, fighting viruses — and perhaps ending disease forever,
- invisible surveillance devices that provide battlefield intelligence, monitor industrial processes — or track political dissidents,
- agriculture nanobots that run super-productive farms, or solar-energy-conversion nanobots that provide essentially free energy,
- nanocomputers and nano-storage devices that open a world where most human productivity moves online.

The above systems can be considered as heterogeneous materials and/or structures at the micro, nanoscale level. In order for these materials to be operational the integration of several functions (mechanics, electrical engineering, electronics, optoelectronics, optics, sensor technology, actuation technology) in one unit is of increasing significance.

The principle of functional integration has already been addressed in the engineering sciences for some time. An optimum combination of actuation technology, sensor technology and microelectronics leads to low-cost and efficient products. Aspects of informatics and control engineering are also considered since large-scale integrated electronic systems are powerful enough to establish increasingly complex programs for the implementation of control algorithms, man-machine interfaces or for signal processing with only a few electronic devices. In many cases, however, considerable deficiencies become apparent with respect to the materials available - in part, due to conflicting property requirements, such as stiffness, flexibility; thermal resistance, heat dissipation; electrical conductivity, electrical insulation; environmental compatibility; reliability; compatibility of material properties and production stages.

The aforementioned strategic directions for Heterogeneous Materials and Structures could lead in significant advances in engineering and applied sciences. For example, within the scope of the nanotechnology initiative, improved simulation and modeling capabilities may emerge by synergistic use of tools from continuum mechanics, statistical mechanics and "other" mechanics; or, applications of homogenization tools to develop improved constitutive models, accounting for the microstructure evolution, for granular media and compacting powders, building up on currently available micro-mechanical and statistical models.

Referring to the biological materials one could argue that the development of smart material systems analogous to muscle tissue and control of such systems, should be revisited from a mechanics point of view. Although not completely novel, this is a problem where mechanics may provide the key to the understanding and further development of such systems. While it may be difficult to achieve the versatility of muscle tissue with a single-phase smart material, such as an SMA single crystal, it may be possible to get closer to the answer by making hierarchical composites of such materials, possibly with other standard materials. For example, the SMA could be turned into a polycrystalline wire, which in turn could be embedded in a rubber elastic matrix, to form an aligned fiber structure. The current through the wires could then be used to achieve controlled three-dimensional deformations of the material. While such a system would be limited by practical considerations (the rubber matrix would act as an insulator preventing the dissipation of heat), it serves as a model of the type of hierarchical materials that may be feasible by careful blending of currently available technologies.

Also, further advances are necessitated in more traditional applied mechanics and materials fields. Recent results indicate that fiber prestress, applied prior to and released after matrix cure can substantially increase damage resistance of composite laminates reinforced by either aligned or woven fibers. Moreover, prestress improves fiber alignment and thus enhances compressive strength of fibrous plies. In RTM fabrication, prestress stabilizes the reinforcement in position. Forces needed in applications are smaller that 130 lbs, which can be generated by available filament winding or fiber placement equipment. Research of this approach, together with modeling of related fabrication procedures can be very helpful in damage retardation and control in composite structures.

Moreover, almost all engineering applications call for multiscale integration. Even if a group of scientist designs a nanorobot, ultimately this will be used in a larger structure. To this extent, methods should be developed that will enable transformation of diverse physical phenomena into common interaction space. For instance, many problems in heterogeneous media involve interaction of several diverse physical processes. Such problems are encountered in modeling of both established composite materials, such as inelastic composites with developing damage, and more recent material systems, such as smart materials -piezocomposites and shape memory alloys, as well as nanocomposites and nanomaterials in general. Many problems in heterogeneous media involve interaction of several diverse physical processes. Interactions and couplings in such systems are often very complex within each length scale, and taking place at several length scales, hence their understanding could be advanced by transforming their effects into equivalents in a common interaction space. For example, such transformations have been accomplished with the transformation field analysis method in problems involving thermomechanically driven damage evolution in inelastic systems, where all thermal, decohesion and inelastic processes can be modeled by equivalent eigenstrains acting on an undamaged elastic system. Similar transformations can be accomplished in piezoelectric and pyroelectric composites. Further research in this area, with focus on nanoscale and hierarchical interactions should open new avenues of understanding of interactive and coupled phenomena.

Finally, the words of Richard P. Feynman can summarize the importance of the proposed promising research directions for composite materials and applied mechanics:

…What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can't see exactly what would happen, but I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do…

[iii] "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics" by Richard P. Feynman , http://www.zyvex.com/nanotech/feynman.html

XXIV

Granular Materials

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As in many areas of Mechanics, the problem of greatest interest in the mechanics of granular materials is the prediction of failure. The two most important forms of failure in granular materials are the catastrophic collapse of slopes, which often result in landslides, and the liquefaction of a soil, with the accompanying loss of its bearing capacity. Both typically occur in saturated aggregates and often are associated with earthquakes.

Slope failure usually occurs in localized regions of intense shearing called shear bands. An active area of research is aimed at predicting the onset of shear bands, their orientation, extent, and thickness and the properties of the flow within them. This effort involves physical experiments on idealized materials, computer simulations that incorporate the dynamics of thousands of interaction grains, and continuum models based in phenomenology or micro-mechanics.

Liquefaction is associated with volume changes that usually accompany shearing in granular materials. Loose packings of fluid-saturated aggregates decrease in volume upon shearing, compressing the interstitial fluid and increasing its pressure. The accompanying reduction of pressure in the solid skeleton permits frictional sliding at contacts, permitting further rearrangement of the structure, additional decrease in volume, and further increases in fluid pressure, until the aggregate looses all resistance to shearing.

The early phenomenological equations that were used to describe the rate independent deformations of granular materials are similar to those employed in metal plasticity with two important differences. The volume of the material is permitted to change as it is sheared; and, because of the presence of fiction in the interaction between particles, the flow rule is non-associated. That is, increments of strain are not, in general, required to be normal to the yield surface.

Such equations applied to monotone loading have the capacity to predict a bifurcation from a homogeneous deformation to bands of inhomogeneous shear at values of the shear stress and at orientations to the principal axes of stress that are close to those observed in experiments. However, loading along more complicated stress paths, including stress reversals, indicate that anisotropy associated with frictional sliding and/or particle rearrangement requires a more complicated description that incorporates the history of the loading. Incremental relations between stress and deformation that include a dependence on the state of the material have been proposed to incorporate the observed dependence on path. The state variables provide the information necessary to link the increments in stress and deformation; they also evolve as the material is deformed. In such a formulation, yield surfaces may be replace with incremental relations that change rapidly at certain values of the state variables.

Micro-mechanical modeling of granular materials focuses on arrays of particles that interact through elastic and frictional forces. The goal is to identify the appropriate state variables from the consideration of force and moment equilibrium of the individual particles, to predict the dependence of the increments in stress and deformation upon them, and to describe their evolution with deformation. What is required is an appropriate incremental relation between the contact force and the displacements and rotations of individual particles and a description of the statistics of the contact geometry and the contact stiffness in a typical neighborhood. Then, a relation between the increments in displacements and rotations and the increment in average deformation is obtained by satisfying the equilibrium equations in an approximate way. With this, and an appropriate definition of the stress in terms of an average over contact forces, the desired relation between the increments in the stress and the average deformation may be written down.

Perhaps the most important recent development in the mechanics of granular materials has been the introduction of computer simulations to describe the equilibrium of random arrays of particles that interact through elastic-frictional contacts. A typical numerical simulation involves the dynamics of thousands of particles confined in a region of given size and shape. Static states are obtained as long-time limits of dynamic states. Periodic boundaries are often employed in order to focus on the response of the material to homogeneous deformations. Such simulations are being used both to simulate problems of practical interest directly and to provide information to assist in the development of micro-mechanical models.

The results of physical experiments on idealized granular materials, such as aggregates of glass spheres with a known distribution of sizes, are beginning to be compared with the results of such computer simulations. These comparisons provide tests of the contact forces employed in the numerical simulations. They also provide an indication of the appropriateness of the initial state used in the simulation in relation to that in the experiment.

With the knowledge at hand, it is not possible to say if isotropic random arrays with the same porosity, confining pressure, and coordination number, generated in different ways in two simulations, will require the same increment in stress to provide the same increment in deformation. That is, we do not know what additional state variables are required to characterize even so simple a state. This problem of characterizing the initial state is one that should be solved shortly.

The hope is that, after having identified the appropriate state variables, it will be possible to measure them with probes of the average mechanical properties of aggregate such as sound waves. This, with a more developed understanding of the incremental behavior, should lead to the prediction of the formation of shear bands and the onset of liquefaction. It will also provide for the possibility of testing soils in place to determine the likelihood of their failure.

In conclusion, at the present time, we seem to have an appropriate way to think about the modeling of granular materials and a tool that should permit extensive numerical experimentation; so there is reason to be optimistic.

XXVI

Report on Foams

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Foam refers broadly to “cellular” solids whose distinguishing characteristics include low density, microstructure, and multi-functionality. Familiar examples such as honeycomb, sponge, and flexible polyurethane foam, which cushions your seat, illustrate the fact that these materials are, to varying degrees: cellular, regular or disordered, open or closed cell, and anisotropic. The continuous solid phase can be polymeric, ceramic, metallic, biological, even edible. Lower density, in general, reduces stiffness and strength, and increases the ultimate compressibility of foams. The standard text on foam structure and mechanics is Gibson & Ashby (1997). A comprehensive survey on the mechanics of cellular and other low-density materials by Christensen (2000) is a key entry point to the recent literature.

The dependence of mechanical properties on density for a specific material is very sensitive to foam microstructure, which may be disordered but is certainly not disorganized. The diversity of foam structures that exist or are desired stems from the broad range of familiar and novel, materials and manufacturing processes that are available; this diversity is responsible for the benefits and challenges of foams. Developing and understanding structure-property-processing relationships is fundamental to this field. The need to quantify foam microstructure pushes the capability of sophisticated experimental techniques such as x-ray tomography and magnetic resonance imaging, which offer substantial advantages over traditional optical microscopy. The morphology of the solid phase, especially in polymeric foams, often differs substantially from bulk materials. A critical need centers on the development of experimental techniques to probe the mechanical properties of the solid; this is particularly challenging because the characteristic length scales of foam features lie in the micron to millimeter range, and, understanding linear, nonlinear, and failure behavior are important.

Foam micromechanics has an obvious role in developing the scientific basis for structure-property-processing relationships. The mechanics problems are particularly challenging and computationally demanding because they involve large deformations of nonlinear material arranged in complex three-dimensional structures. Simulations that include multiple physics and length scales will continue to benefit from developments in computational science. Significant effort is focused on the development of constitutive equations for foams. It is widely recognized that instabilities develop locally and spread with increasing load, causing localization under large compression. Experimental and theoretical studies by Papka & Kyriakides (1998) on in-plane strength and failure mechanisms of honeycombs set the stage for extension to three-dimensional loading and materials. The role of material inhomogeneity, boundary effects, and imperfections that result in loss of material integrity, are also important areas to investigate. Traditional continuum mechanics approaches and homogenization techniques are not adequate to deal with many of these issues. As the inevitable role of foams in MEMS technology evolves, related issues of scale will arise as cell size approaches that of devices.

Foam science and technology provide rich opportunities for interaction between traditional solid mechanics and fluid mechanics in the realm of processing because many foams begin life as gas bubbles growing in viscous fluids that eventually solidify. Consequently, viscosity and surface tension, at the very least, influence the evolving foam structure. Boundary element methods can be used to model the fluid mechanics of foam growth as well as the solid mechanics of the final structure, which touches on all corners of the structure-property-processing triangle. Simulations such as these are needed to interpret experimental data on foam structure. They also provide insight into the degree to which the microstructure can be controlled during processing. Physics, chemistry, materials science, and mathematics also play crucial roles in this highly interdisciplinary field (Weaire & Hutzler, 2000).

“Two-dimensional” materials such as honeycombs are inherently anisotropic. Advanced microfabrication techniques have led to the development of three-dimensional lattice-block structures that are significantly stiffer than conventional open-cell foams due to higher strut connectivity. Designed lightweight materials offer enormous potential in demanding applications that required high multi-functionality.

Foam mechanics applies to biomaterials such as trabecular bone and lung parenchyma, as well as artificial organs and limbs. A micro-mechanical point of view is extremely useful in understanding the wide range of transport phenomena that influence the function of healthy and diseased organisms. Mechanical behavior is one of many critical issues in biomedical systems, which are inherently multi-functional. Specialty polymeric foams have found a significant market in advanced wound treatments for severe burn victims.

A project on Ultralight Metal Structures that was supported by the DARPA/ONR MURI program involved strong international interactions between government, university (Harvard, MIT, UVA, Cambridge), and industry. The project resulted in significant scientific advances in foam processing and mechanics, as well as the publication of the text *Metal Foams: A Design Guide* by Ashby et al. (2000). Strong commercial interests that drive R&D in this rapidly developing subject can be followed on the Web at www.metalfoam.net. Europe leads the world in level of activity on foams in general and on metal foams in particular. The past decade has witnessed several EuroConferences, a NATO Advanced Study Institute, two MetFoam Conferences, a workshop sponsored by the European Space Agency, and other foam-related technical meetings.

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XXVIII

Fracture and Fatigue

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Failure of structures and materials through fracture was brought to the fore by spectacular failures of ships, airplanes, bridges, pipelines and other engineering structures. Among the more famous examples, molasses tank exploded in Boston wreaking havoc, Liberty ships broke into two at port on cold days, Comet jet aircraft disintegrated in flight, and miles of pipelines have been rendered useless by cracks. Driven by the economic and social pressures of such costly failures, research into understanding and controlling fracture flourished over the second half of the twentieth century. As a result of these efforts, a strong foundation in the methods aimed at evaluating structures with cracks has been laid. There are three main ingredients that form the core of this methodology:

- the detection of flaws in the structure (the domain of nondestructive testing),
- an assessment of the material properties (the domain of materials and standards developers), and
- an evaluation of the environment – mechanical, thermal, chemical – that the structure will be subjected to in its projected life.

Solid mechanics researchers have provided much of the leadership in solving these problems and will continue to be involved in advancing our understanding and use of fracture critical structures. The legacy of this effort is that today damage tolerant structures are routinely designed and operated safely. Thus, it would appear that fracture mechanics is a rather mature field, with a very successful transition of the technology to industrial practice. This would be true but for the fact that the success of fracture mechanics has been spectacular only in nominally homogeneous materials and furthermore only as long as inelastic deformations near the crack are limited to domains that are small in comparison to other significant length scales in the problem – within the constraints of the so-called small scale yielding. An unintended consequence of the damage tolerant design approach is that there are currently many structures – airplanes, pressure vessels etc – that are well beyond their lifetime predicted using fracture mechanics methodology! The root cause of this underprediction is, of course, that we have been extremely conservative in the fracture assessment methodology. Since it is enormously expensive to replace the aging infrastructure all at once, one would hope to improve on the life assessment techniques. For example, the current fleet of airplanes that are operated by US airlines is more than twenty years old, with the number of take-off and landing cycles near or exceeding the design life of about 90,000 (check number) cycles. Yet, these aircraft seem to be viable structures; the question to be answered is whether our knowledge of the state of damage, material properties and failure models is adequate enough to guarantee (ensure) the safe operation of these aircraft beyond their initial predicted life. Future research in fracture must therefore focus on aspects of the problem that go beyond the linearly elastic fracture mechanics (LEFM) approach. With this in mind, we have assembled a list of ten priorities, not necessarily in order of importance. Note that there might be other issues that might be of importance in specific applications, but the areas listed here would appear to have a large range of applicability to the design of fracture critical structures.

- *Failure nucleation*

In implementing the LEFM approach to failure prediction, it is assumed that pre-existing cracks in the materials grow through accumulation of damage under repeated loading, and eventually reaches critical dimensions resulting in structural failure. The assumption of a preexisting crack completely avoids the nucleation of flaws in the material under loading. However, it is well recognized that most systems spend a significant fraction of their lifetime in the stage where flaws get nucleated from defects at the microstructural level and become identifiable cracks for which the fracture mechanics analysis is well suited. This is one of the primary reasons for the underestimation of the lifetime of the structure. Furthermore, in microelectromechanical systems (MEMS), considering that the structural dimensions are comparable to the microstructure/defect dimensions, there might not be any significant life left after a flaw gets nucleated; the problem of crack nucleation is the only fracture problem that is relevant in this case. Thus we believe that it is essential to focus research efforts toward understanding, characterizing and modeling the crack nucleation problem. Underlying crack nucleation are deformation and localization mechanisms such as cavitation, shear banding, grain boundary sliding, delamination, and other such mechanisms. New tools such as the scanning probe microscopes and high resolution transmission electron microscopes that have been developed over the last couple of decades and new experimental capabilities for quantitative measurements at length scales that are at the level of the grains and grain boundaries (see the section on Experimental Mechanics) permit greater access to detailed investigation of the crack nucleation problem

- *Failure in heterogeneous materials*

Increasing demands on structural performance of materials that are at the same time light in weight (for both cost and performance related reasons) has driven the development of multiphase materials. After decades of development of laminated composites, current performance requirements are steering new developments towards woven composites to enhance out-of-plane strength and circumvent delamination failures. Functional integration and design complexity in microelectronic circuitry has also driven the technology towards multilayered, multiphase materials. Biological materials perform this kind of multilayered, multiphase material constructions almost exclusively. In evaluating the behavior of such materials or systems, much progress has been made in understanding the mechanisms of deformation and damage accumulation. Effective elastic properties, tensile and compressive strengths and their degradation are all reasonable well modeled. While the fracture mechanics developed for homogeneous materials is not appropriate here; the heterogeniety of the material makes the idea of a dominant flaw unimportant. However, a methodology for evaluating the strength, flaw-tolerance, and lifetime of a damaging (not necessarily cracked) structure is still an important ingredient in engineering with these materials. The failure behavior under dynamic loads has only recently been examined and much remains to be investigated.

- *Design of heterogeneous materials*

The approach to using heterogeneous materials in structures has been to follow the conventional approach of determining stiffness, strength, ductility etc as in homogeneous but anisotropic materials and then to perform an analysis of the stress and deformation state to evaluate suitability of designs. An inverse problem, one that could radically alter the penetration of composites into practice, would be to consider tailoring the heterogeneity and anisotropy to particular applications; this is in some sense “biomimetic” – biological materials adapt their structure to function (for example, Wolff’s law for bone anisotropy). This idea has received some attention within the mathematical optimization community, but not much within the mechanics and materials groups. We suggest that an integrated examination of this including the perspective of constituent material properties, processing methods and structural analysis will result in revolutionary advances in the design of heterogeneous materials.

- *Nonlinear fracture mechanics*

As we have described above, LEFM is quite conservative and results in a significant underprediction of the lifetime of structures. And in some applications such as in the layered materials used in microelectronic or in accident simulations for automobiles and other structures, nonlinearity is inherent in the problem and must be incorporated into the analysis. Much of traditional fracture mechanics (linear as well as nonlinear) has been focused on analyzing the ‘outer problem’ of determining the stress, deformation and energy flow in a region near the crack tip. However, in order to determine the failure properties, one needs to examine the ‘inner problem’ of understanding, characterizing and modeling the failure processes that actually lead to energy dissipation. Recent developments in incorporating an explicit fracture process zone model as a representation of the ‘inner problem’ [for instance the cohesive zone models] have made numerical simulations of nonlinear fracture problems reasonably easy to accomplish. But, there arises the question of determining the properties of these models – experimental characterization of the fracture process zone at length scales that are on the order of the dimensions of the fracture process zone.

- *Friction, slip dynamics*

At first glance friction might not appear to fit into the classification of fracture problems, but recent investigations on single and multi-asperity contacts and slip dynamics reveal a strong connection to fracture mechanics.

ballistics
delamination
geomechanics
Schallamach waves

- *Bridging scales*

Fracture is a phenomenon that occurs at the smallest scales – the rupture of atomic bonds – but manifests itself at the microscopic to macroscopic scale (MEMS devices to human scale to geological scale). Therefore this problem presents the ideal testbed for bridging scales in simulations. While atomistic models today are getting more powerful and able to simulate events on the scale of nanometers, experimental tools have also advanced enabling investigations of fracture phenomenon at sub micron scales. We believe that it is possible to develop fracture models that scale from the atomistic to the microstructural to the macroscopic scales. This would really build the connections between the ‘inner’ and ‘outer’ problems described in item 4.

Research effort in this direction would be a fruitful endeavor for mechanicians from experimental, theoretical and computational aspects.

- *Material-specific problems*

While solid mechanics aims to provide a global representation of fracture regardless of material, the different mechanisms of deformation and fracture that different materials exhibit require that special models be developed for specific material systems. Thus, for bulk metallic glasses, textile composites, polymers (systems far from equilibrium) and a whole host of engineered materials, investigations on the mechanisms, and development of constitutive and failure theories are needed. Bulk metallic glasses appear to exhibit superior strength and toughness properties compared with other intermetallics; however, their fatigue performance. Polymers are a class of materials that are far from equilibrium and evolve as a function of time, temperature and loading. They are also susceptible to the environment – moisture, radiation etc. Methods for assessing the durability of structures made of polymers and their composites are not well developed; nonlinearity inherent in the material behavior near failure also needs to be examined.

- *High strain rate failure*

blast confinement
pipeline rupture
penetration
inertia effects rate dependence

- *Shear coupling in cracks*

LEFM, while well entrenched into industrial practice, still has some gaps in its completeness. It has been assumed in almost all crack growth analysis that the dominant crack would somehow find the path that will keep it in a state of a locally symmetric (mode I) deformation. Furthermore, LEFM predictions are often limited to cracks that can be regarded as two-dimensional. However, subsequent to nucleation, and prior to development as a through-the-thickness 2D crack, there is a stage in the life of a crack when it is truly a three dimensional entity, subjected to a combined opening, shearing and tearing mode loading. Currently, there are no accepted methods for predicting the growth of cracks under such loading. If nondestructive crack detection schemes are advanced enough to detect small part-through 3D cracks, fracture analysis should keep pace in predicting the growth of such cracks. Friction along the crack surfaces when in contact will also play a crucial role on determining the crack path, growth, and stability.

- *Nonlinear dynamics*

Fracture is a critical phenomenon; even in nominally brittle materials, the microscale processes that generate crack growth interact in interesting ways that generate a rich range of dynamics. For example, crack growth and crack path selection in a quenched glass plate exhibits interesting bifurcations; dynamically growing cracks generate surface disturbances that possess soliton-like characteristics. If the fracture process is modeled as a nonlinear dissipative mechanism, then the solution of the complete fracture problem – the external loading plus the internal dissipation – will certainly exhibit evolution whose dynamics merit serious study.

XXXII

Tribology and Contact Mechanics

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Introduction

The study of friction, lubrication and wear, or tribology, has a long history and has served a crucial role in the development of technology, since ancient times. Closely linked to tribology is the field of contact mechanics, which focuses more specifically on how contacting bodies deform in the vicinity of their mutual interface. Great progress has been made in these areas over the past few years and ongoing research promises to make significant contributions to the advancement of numerous technologies. In particular, one finds exciting new developments with micro- and nano-scale devices, specialized coatings and lubricants, methods of material characterization, techniques for surface analysis, and methods of computation. Despite the achievements in these areas, there remain a number of key unsolved problems in both tribology and contact mechanics. Ironically, researchers have yet to develop first-principle theories to handle the most basic questions in tribology, namely those that relate to the nature of friction and wear. Additionally, gaining a good understanding of boundary lubrication—where lubricant films approach molecular dimensions--remains on the list of problems to be solved. This paper describes some of the recent advances in the tribology and contact mechanics arenas, identifies some of the outstanding problems, and proposes some future trends.

What's New

In discussing what is new in tribology and contact mechanics, we focus on both new developments as well as knowledge newly-applied to these areas.

- *New Applications*

Relentless technological advances yield more and more applications where tribological phenomena may play important roles. We consider some of these below.

- *Mems*

There has been substantial activity in the past ten years or so in the MEMS (micro electro-mechanical devices) area and this has led to the investigation of tribological problems associated with the operation of such devices. New challenges are presented by MEMS because of the relatively large role that surface forces play with these small-scale devices. This has led to renewed efforts to understand and solve the problem of adhesion, which, in turn, has spurred development of the novel types of monolayer coatings. These coatings are generally geared to passivate the surfaces and thereby reduce the driving force for adhesive interactions.

- *Microelectronics*

The field of microelectronics has been around for decades, but the continued push for high numbers of electronic devices within a chip requires that surfaces be developed with greater and greater flatness. That is, developing the various interconnects between successive layers requires that each layer achieve a high degree of planarization. This need has motivated research in chemical-mechanical polishing (CMP), which, among other things, has revealed the role that negative hydrodynamic pressure plays in the material removal process.

- *Magnetic Recording*

The ever-increasing demand for greater information storage capacity in smaller and small form factors has led to the introduction of precision tailored interfaces. Magnetic recording disks found in commercial disk drives are now equipped with laser-zone texture, which consists of a regular pattern of nanometer-scale bumps, fabricated in the "parking" zone of the disks. The presence of these bumps helps to control "stiction," between the read/write head and the surface of the disk. (Stiction is the term used to describe static friction forces--particularly when they are mediated by a thin film of liquid via capillary effects.) The bumps provide a means to control the way that capillary films are formed in the interface.

- *New Materials*

Achieving desired performance can sometimes only occur with the development of novel materials. Such new materials are often created to mitigate or solve a tribological problem. We describe some instances of this below.

- *Advanced Coatings*

An interface, by definition, exists at the surfaces of the contacting bodies. Therefore surface modification can serve as an effective means of achieving desired surface performance. Advanced coating technology is presently used for various applications. One example occurs in the magnetic recording industry, where diamond-like carbon (DLC) films are deposited on top of the magnetic layer to protect it from physical contact with the read-write head. Additionally, the read-write head itself is often equipped with a DLC film. Coating technology is often applied to manufacturing processes where there is a need to minimize adhesion processes during the formation of metals and other materials. In these instances, the coatings are required to sustain extreme (hot) temperatures.

Another example of advanced coating technology occurs in the biomedical industry, where synthetic hydrogels are under investigation for possible replacement to joint cartilage. Joint cartilage in humans and animals is a type of low-friction, low-wear coating that covers the load-bearing members of the joint. Synthetic hydrogels, essentially cross-linked hydrophilic polymer networks, show promise as a better-performing alternative to commonly used ultrahigh molecular weight polyethylene (UHMWPE).

- *Lubricants*

Most of the recent progress in lubricants has been in the form of lubricant additives. In the automotive industry, these have served to further reduce friction and wear and reduce toxic emissions. In the magnetic recording arena, new additives have shown promise as agents to substantially improve the durability of magnetic disk surfaces as the lubricant films and overcoat layers become thinner and thinner.

New Measurement Methods

Attaining increased insight requires new information, which often depends on the development of new ways to measure effects and properties. In this section we highlight some important measurement techniques that have contributed significantly to our understanding of tribological interactions.

- *Optical Interferometry*

In the past several years there has been significant progress in the ability to measure the thickness of very thin lubricant films. Currently, measurements have been reported of elastohydrodynamic (EHD) minimum film thicknesses of only a few nanometers. This research has helped reveal the role of boundary lubricant additives in the formation of protective surface films during high-pressure contacts. Even more refined measurements of lubricant film thickness have been accomplished with the surface forces apparatus (SFA), which utilizes cleaved mica sheets to provide molecular smoothness within a Hertzian contact. Research with this device has contributed to the understanding of lubricant behavior down to monolayer thickness. Additionally, because the SFA affords the ability to view the contact region, SFA experiments have provided important insight into the nature of frictional interactions on a micro-scale. The SFA has also been used to verify the JKR theory of adhesive contact. Optical interferometric methods are also important to the determining the flying characteristics of read-write heads on magnetic disks. Recent developments allow for flying heights to be measured that are only a few tens of nanometers.

- *Atomic Force Microscopy*

Since the advent of the atomic force microscope (AFM) a little more than a decade ago, there have been extensive investigations into topography, contact, friction and wear with an atomic scale interface. The AFM slides sharp stylus over a surface and attains atomic-level resolution in both horizontal and vertical dimensions, thereby providing a high degree of surface detail. Additionally, as a friction force device, the AFM provides a means to investigate “single asperity” interactions. More recent extensions of AFM usage include employing the AFM as a manufacturing tool to fabricate desired patterns with atomic resolution.

- *Surface Analysis*

In recent years a number of surface analytical methods have been employed and refined to provide insight into tribological interactions. Some of the important ones include Auger electron microscopy (AES), scanning Auger microscopy (SAM), Raman spectroscopy, and the contact potential difference (CPD) method. These techniques are used to identify the nature of tribologically-induced chemical reactions as well as to characterize the nature of films that form on the surfaces of interest.

New Computational Methods

As available computational power continues to enjoy rapid growth, an increasing number of tribological phenomena become viable candidates for extensive computer modeling.

- *Computational Fluid Dynamics*

Computational fluid dynamics (CFD) has been employed to study lubrication problems using the Navier-Stokes equation as the starting point. It therefore represents an improvement over reliance on the more simplified Reynolds equation. Moreover, CFD calculations can be used to assess the range of applicability of the Reynolds equation.

- *Molecular Dynamics*

Molecular Dynamics (MD) simulations involve calculating the trajectories of atomic particles within a solid, liquid or gas. Such computations are able to reveal interactions that continuum-based models are unable to resolve. Because MD, by nature, operates on the time scale of atomic interactions, typical MD simulation times represent less than a nanosecond of real time. Nevertheless, MD simulations have provided important details on how contacts are formed and broken. Because MD simulations deal with the atomic particles themselves, they attain the ultimate in temporal and spatial resolution.

- *Multi-Grid Methods*

Multi-grid methods are now widely used in to solve the Reynolds equation of lubrication, particularly in EHD contacts. The multigrid method provides a great advancement in convergence rate for finite difference algorithms that iterate on the values of pressure. By employing these computation methods, researchers are able to develop more complete simulations of lubrication processes. In particular, the roles that surface roughness and surface elasticity play in EHD contacts are becoming increasingly clear.

- *Variational Methods*

The study of contact with both smooth and rough surfaces is being facilitated by the application of variational methods. These methods provide superior robustness and computation efficiency when compared to traditional finite difference formulations. Moreover, when a variational method is applied in conjunction with the Fast-Fourier Transform (FFT) algorithm, a marked reduction in computational time is achieved. Consequently, contact simulations are now able to incorporate a more detailed depiction of surface topography.

- *Unsolved Problems*

Despite the significant strides that have been made in tribology and contact mechanics, there are a number of basic problems that remain unsolved. A few of these are outline below.

Theory of Friction

While there are numerous empirical and semi-empirically based models of friction, there is not, as of yet, a theory that is able to accurately predict the friction force. That is, given two bodies of known material composition, known geometry, known temperature, and known surface topography, sliding under a known load, at a known speed, one cannot predict what the friction force will be. In other words, there is no accepted formula that relates friction to the aforementioned material characteristics unless it also contains a parameter that is obtained from a friction measurement itself. Developing such a theory would be of great benefit to designers. Since friction is ultimately a means by which mechanical energy is converted to thermal energy, attaining a successful theory of friction relies on understanding the way that mechanical energy is dissipated within a body. Perhaps MD simulations offer that greatest hope to achieving this goal.

Theory of Wear

Most of the comments made regarding the development of a theory of friction can be equally applied to wear. There are indeed phenomenological models of wear (e.g., Archard's Wear Law), but these involve adjustable parameters whose values have not been successfully related to intrinsic, measurable material properties.

Boundary Lubrication

Full-film hydrodynamic lubrication is quite well understood, as evidenced by the fact that theoretical predictions are borne out by experiment. In contrast, boundary-lubricated interfaces, where the film consists of only a few molecular layers and where the load is shared between the solid-solid and liquid-solid contacts, is not well understood. One major difficulty in modeling such a regime of lubrication is that the properties of lubricant films are not generally known at typical operating conditions. For example, nanometer-scale films sheared at even moderate sliding speeds sustain extreme shear rates—much higher than those attainable in a controlled test. Consequently there is a lack of information upon which to build a model of the interface. Substantial progress toward a solution of this problem awaits advances in measurement capability.

Future Trends

In the remaining portion of this paper, we conjecture as to the likely areas of focus and development in the next 5 to 10 years.

- *Tribo-Visualisation*

The computer-visualization techniques that are common in general CFD studies as well as with MD simulations will become more commonplace for a wide range of tribological interactions. These techniques will assist researchers and designers in achieving sound physical insights into tribological interactions.

- *Tailored Surface Topography*

The last few years have witnessed the laser texturing of magnetic hard disks to achieve the required tribological performance. The idea of fabricating a desired surface topography for a performance objective is quite attractive. It is anticipated that a number of new methods will be forthcoming to advance this technology.

- *Integration Between Scales*

There is extensive tribological research being conducted at macro, meso, micro, and nano scales. However, there is, at present, a lack of integration among the different scales of operation and investigation. It is expected that there will be increased interaction among the various camps and approaches.

- *Integration Between Disciplines*

Tribology continues to be a highly interdisciplinary field. However, a many researchers are heavily biased toward a given discipline in their approach to solving tribological problems. In the future, a greater and greater emphasis will be made on solving tribological problems from a broad, interdisciplinary perspective.

- *Tribological Databases*

In recent years, there have been substantial efforts to develop databases of material properties, including those containing tribological information. With increasing accessibility to information, it is expected that a growing market will develop for relevant tribological data over the Internet. It is envisioned that machine designers will increasingly rely on up-to-date electronic resources for solving system design problems.

XXXVIII

Tribology and Nanotechnology

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Introduction

Perhaps no physical phenomenon is more common yet less understood than friction. We routinely encounter and rely on its effects, from the act of walking to the operation of machines. Its impact is felt economically as well: energetic and mechanical losses due to friction and wear are estimated at 5-10% of industrialized nations' gross national products[1]. Yet a fundamental, predictive description of friction remains elusive.

Tribology, the study of friction, adhesion, wear, and lubrication, addresses problems found in countless macroscopic applications, from automotive parts to aerospace components to orthopedic implants[2,3]. Tribological problems become even more severe as technological scales shrink and correspondingly the surface-to-volume ratio of the material or device greatly increases. Surface forces like friction and adhesion become dominant interactions, imposing serious performance limitations. This point is painfully appreciated by the microelectromechanical systems (MEMS) community, who have found that MEMS devices are critically limited by interfacial adhesion-, friction- and wear-related failures[4].

Thus, these effects are thus most critical at the nanometer scale. We make two important assertions here: (1) progress toward the implementation of nanomaterials technologies will not occur without a fundamental understanding of frictional energy dissipation at interfaces; and (2) understanding and control of friction will enable new nanoscale technologies.

Research Highlights

The last ten years have seen the rapid emergence of *nanotribology*. A number of key developments have aided the growth of this field:

1. development of the atomic force microscope (AFM) which allows the measurement and application of nanoNewton scale forces.
2. extension of the quartz crystal microbalance (QCM) to measure friction between adsorbates and surfaces.
3. extension of the surface forces apparatus (SFA) to measure friction between molecular films.
4. emergence of molecular dynamics (MD) simulations whose simulation cells are nearly equivalent in size to AFM and other experiments. This has occurred thanks to advances in computer power and software code development.
5. emergence of *ab initio* studies of tribology where, again, the calculations cells are nearly equivalent in size to AFM and other experiments thanks to advances in theory, code, and computer power.
6. a rapid development in methods to synthesize nanomaterials such as nanotubes, nanowhiskers, nanocomposites, nanofabricated structures, self-assembled monolayers, *etc*.

There a number of spectacular results that have emerged in the field of nanotribology, several of which we summarize here:

1. direct manipulation of nanoscale materials, such as carbon nanotubes, and measurement of their tribo-mechanical properties. Nanotubes can be moved and rolled on surfaces and the

required shear force measured[5,6]. They can be attached to AFM tips and have their axial loading properties measured[7,8], or can be used as an imaging probe[9,10].

2. quantitative measurements of friction at the nano-scale using AFM for a range of materials. This has allowed the determination of the interfacial shear strength (friction force per interfacial atom) and the interfacial work of adhesion (adhesion energy per atom)[11-15]. The primary result is an excellent agreement with contact area predictions of continuum mechanics even at the scale of a few nanometers.
3. precise measurements of the tribo-mechanical properties of monolayer organic films. Organic self-assembled monolayers (SAMs) are extremely important materials for nanotechnology. They provide a method of tailoring the chemical, structural, and mechanical properties of surfaces at the molecular scale[16]. Inert SAMs have excellent lubricating properties and are being successfully used as lubricants for MEMS[4,17]. Hydrocarbon SAMs are closely related to boundary lubricants used in macroscopic contacts. Because they form densely packed and often ordered structures on solid surfaces, SAMs are ideal to model lubricant films for fundamental studies of tribology. They are also being used for multiple nano-scale applications to provide surface functionality[18,19]. It is therefore critical to determine the tribological characteristics of SAMs. Some recent highlights include:

   -direct correlation between friction and hydrocarbon chain length
   -changes in friction as a function of the terminal chemical group in the monolayer[20-22]
   -the ability to cause and observe a structural transition in a monolayer at the nanoscale using shear forces applied by the AFM tip[23]
   -observation of friction anisotropy that is associated with the film structure[24,25]
   -observation of quantized compression of SAM films[26]

4. evidence for electronic contributions to friction. Coupling between the electron density of conductive sliding surfaces produces a frictional drag force, similar to that which causes an increase of resistance by the presence of surfaces in thin films[27]. The theoretical basis of this electronic dissipation has been discussed in some detail and recent experiments, particularly with the quartz crystal microbalance (QCM), indicate that electronic dissipation can be the dominant contribution to friction in certain instances[28,29]. The experimental evidence is based upon QCM measurements of ultrathin (< 2 monolayers) adsorbate films sliding at high (MHz) frequencies on conductive surfaces. In these experiments, there is no applied mechanical stress, although there are certainly surface and interfacial stresses that result from adsorbate-substrate interactions. A recent atomic force microscope experiment suggests that electronic friction is observable for a loaded nanocontact as well[30].

Key Challenges

Despite these impressive advances, there are several barriers that remain and which need to be overcome before a comprehensive understanding of nanotribology will emerge. This includes:

- the gap of several orders of magnitude between the time scales of MD and AFM experiments
- ongoing friction problems with MEMS that have not yet been fully solved. This does not bode well for the assembly and operation of nano-scale machines.
- calibration problems with the AFM. Many groups do not calibrate their AFM measurements. Uncertainty in force constants and tip shapes render many results unreliable and irreproducible
- lack of any reliable quantum description of friction.

New Ideas, Applications, Technologies

The most obvious application of a fundamental understanding of tribology will be to enable the assembly and operation of nanoscale devices with moving parts. Furthermore, an understanding of nanoscale interfacial forces will enable the development of nanomaterials, such as high-strength nanocomposites (where interfacial friction is a key mechanism for toughening). There are many overlaps with notions in rheology, and the impressive studies of organic materials with AFM indicate that this connection should be explored in more detail.

Instrumental challenges must be addressed. The AFM needs to be improved so that it is more sensitive and more quantitative. Methods for characterizing the AFM tip at the atomic level are required. Higher speed measurements are desirable as well, so that the measurement velocities are comparable to real-world tribological situations.

Multiscale modeling efforts that address the crossover from continuum to quantum mechanics are critical. Already, numerous efforts point out the reliability of continuum mechanics to describe the framework of many nano-scale measurements, but continuum mechanics cannot predict material properties such as the interfacial shear strength. Work that combines continuum and quantum approaches is potentially powerful.

For each of the items above, there are tremendous opportunities for researchers in the mechanics community. Many physicists, chemists, and biologists are becoming interested in the tribo-mechanical properties of novel nanoscale materials, but they lack a detailed knowledge of mechanics that would guide them. We therefore conclude that interdisciplinary collaborations between these researchers and the mechanics community have the potential to enable rapid developments in nanotechnology.

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XLII

Damage Mechanics

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Summary

The primary challenge of the damage mechanics is to demonstrate the essential role of microcracks on the momentum transfer through the damaged structure, mode and proximity of the material and system failure. The task of research in damage mechanics needs to answer this challenge to understand that damage evolution is many times but an overture to brittle failure, faulting and presence of macrocrack.

Introduction

The goal of damage mechanics is to estimate the effect of microscopic defects on the momentum transfer through a damage structure and its residual strength. Of all microscopic defects microcracks are most important in design due to their propensity to propagate in unstable mode. Microcracks that are present in all structures are introduced in manufacturing and in its service.

Damage evolves by random site nucleation of new microcracks, propagation of present microcracks and clustering of these microcracks into fractal objects of complex geometry that are known as macrocrack, shear band, etc. Since the microcrack is of the size of material texture, such as grains in polycrystalline material of particles in a particle-reinforced material, the nucleation sites are randomly distributed within the material while the propagation path depends on the local stresses and material texture, i.e. geometry of planes of weak cohesion.

Needs of Damage Mechanics

Models of damage mechanics, which predict a process and not only fit of a given curve, must be based on the thermodynamics of dissipative processes, statistical physics and fracture mechanics. Since the nucleation and propagation of microcracks depend on the material disorder (i.e. weak spots and planes of random strength, geometry, direction and position) they are statistical processes on the microscopic scale. The assumption that a random process can be approximate by a deterministic process is not always true.

Macroscopic parameters of a model useful in application must be identified and measurable in situ and laboratory. This model must predict the mode and proximity of failure. To define the proximity of a state from the failure at a given load pattern it is necessary to define the order parameter measurable in situ. Finally, the model should be developed in the form that will accentuate the application of computers using large numerical on the shelf codes. This model cannot only fit a deformation process using a handful of fitting macroscopic parameters of obscure physical meaning making their identification and measure difficult if not impossible.

The needs for new models of damage mechanics are illustrate current air design concepts and fatigue mechanics. The damage tolerance aircraft design is based on the probability and reliability of damage detection and estimate of the residual strength of a damage structure. While those concepts are not carefully defined the lament that “the lack of interest and resolve in the research community to characterize and quantify the visual (damage) data is indeed perplexing" (Goranson 1993) is a sign of the increasing gap between industry and academia. The effect of material texture on the propagation of microcracks is dismissed in fatigue design by calling the cracks as being "anomalous", low allowable stresses and plotting data on the log-log scale. The proliferation damage models, based on the imagination, makes the bad state worse.

To answer the industry needs the model must be of the multi-scale type that bridges gap between atomic and microscopic scales, which are intrinsically statistical, to the macroscopic scale that can be either deterministic or statistical. The explosive increase of the computational power will make large scale parallel computing possible even to those that are now using traditional finite element algorithms and codes.

Current State of Damage Mechanics Modeling

Most models published in the available sources are of the mean-field type. A typical traditional local continuum is based on the thermodynamics with internal variables, principle of determinism, material objectivity and local action. Thermodynamics with internal variables assume that each thermodynamic state depends on the small number of macro-parameters, which is true only if the damage parameter can be defined by damage density. Principle of determinism, required that future depends on the past, may be violated when the process is far-from-equilibrium. The principle of local action implies that the effect of micro-defects, randomly within an "infinitesimally small of a material point" of a material point $\vec{x}$, on the macroscopic material parameters (such as stiffness tensor) and fields can be described by an internal (damage) tensor variable(s) $\boldsymbol{D}(\vec{x},T)$. The corollaries to these principles, that are seldom known and ever less considering and interrogate, are that:

- The damage is described by its density,
- The material within the "infinitesimally small of a material point" must be statistically homogeneous.
- The deformation and damage evolution processes can be approximated by a temporal sequence of the equilibrated thermodynamic states.
- Distances between all pairs of these thermodynamic states are "close".

Thus, these models are applicable only when:

- The damage is modest and the band-with of the size distribution of microcracks is small.
- The microcracks are of the size of material texture.
- The representative volume element is not larger than the "infinitesimally small of a material point".
- The damage evolves by microcrack nucleation and the effect of sporadic microcrack stable propagation on the macroscopic deformation is small to modest.

The potential exists only these criteria are satisfied and a continuum damage model can indeed estimate the considered dissipative deformation process. However, all continuum models of damage mechanics are limited in application since they ignore the disorder of the material texture, local fluctuations of stresses and cohesive force on the microscopic scale that affect microcrack propagation and interaction between microcracks. This effect at large damage has a strong influence on retardation, deflecting, branching, stabilization, destabilization, and trapping of microcrack (Suresh 1991).

The mean-field models of micromechanics are an approximate theory in which the variables take on mean or average values and are then calculated self-consistently. Damage material is, in these models, approximated by a large number of microcracks randomly embedded within a continuum elastic matrix. Assuming that damaged material is statistically homogeneous the positions of microcracks are ignored and their size and orientations of microcracks define the damage parameter.

The analytical solution for the volume parameters is possible only when:

- All microcracks are of simple geometry (either a linear slit or a penny-shape microcrack).
- The distribution of sizes and orientations of microcracks are not correlated.
- Matrix homogeneous, isotropic and linear elastic.

In this case the effect of the damage on the volume compliance attributed by the accumulated damage is derived in the form (Krajcinovic, 1996)

$$S^{*}_{ijmn} = w\,\Phi_{ijmn}\left(\bar{S},q\right) \qquad (1)$$

where

$$w = N\left\langle a^{3}\right\rangle \qquad (2)$$

is the Budiansky-O'Connell (1976) isotropic damage parameter. The fourth tensor Φ_{ijmn} is derived integrating the integral of the function of the effective compliance $\bar{S}$ and distribution of the microcrack orientation $q(j\,,J,z\,)$. The effective compliance tensor is then $\bar{S}_{ijmn} = S^{o}_{ijmn} + S^{*}_{ijmn}$, where S^{o}_{ijmn} is the known compliance tensor of pristine volume, and N number of active (open) penny-shape microcracks of radius a.

The most important weakness and limitation of the mean-field micromechanics in the course of the derivation effective parameters of a damaged material is that:

- The effect of many small microcracks is equal to the effect of small number of larger microcracks accordingly to the (2).
- The material texture is ignored even though it is of the microcrack size.

The postulate of local dependence (Rice, 1975), which is also of the mean-field type, is used to deduce the potential needed to estimate the damage evolution. This potential depends on the macroscopic parameters, such as tensile and compression strength on the macroscopic scale, but not on the local fluctuations of stresses and texture disorder on the microscopic scale which affect the morphology and topology of the damage, i.e. nucleation sites, propagation of microcracks and their clustering.

In summary, the tools, models and methods of damage mechanics, in its current state, obstinately focuses on the modest density of microcracks where old tricks of trade borrowed from the venerable deterministic plasticity theory apply. However, the ultimate objective and destination of damage mechanics is to become an overture to the structural failure. One has to confess that the current models of damage mechanics are not useful in estimates of structural failure as observed from the Goranson's lament who does not reference a single damage mechanics paper.

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Statistical Models

It is a truism to state that same physic laws that are valid for a large crack must also be valid for a microcrack even though the latter it is of very complex geometry and "sees" the surrounding material as being non-homogeneous and disordered. Most of us would accept that nucleation and propagation of a given microcrack depends on the local stresses and local cohesive strength rather than volume averages of stresses and cohesive strength of the material. Thus, the concepts of the thermodynamics and fracture mechanics should be remained while the validity of the assumptions of homogeneous material and stress field should be questioned.

The essence of the prior paragraph is that the mechanics of microcracks is not always deterministic, i.e. that the statistical input will always provide deterministic output. Spatial and temporal fluctuations of stresses and cohesive strength in the considered volume of damaged material may be large. Local values of the release energy or *J*-integral and cohesive resistance *R* of a microcrack embedded in the volume in the equilibrium state can be much larger or smaller than the *J* and *R* derived using average stresses and material strength. Common sense is the propagation of microcracks depends on local magnitudes of J_i and R_i. The first microcrack to start propagating after increasing quasi-statically the average stress to magnitude $\overline{s}$ must satisfied the local criterion

$$max_i\left(\frac{J_i\left(x;\overline{s}\right)}{R_i\left(x;\overline{s}\right)}\right)=1 \qquad (3)$$

sought over all *i* microcracks of the volume. The stability of the microcracks propagation is stable depends on the position and magnitudes of energy barriers (local cohesive energy *R*) large enough to decrease the left part of (3) bellow one.

The energy released by a propagating microcrack is distributed to the surrounding material in the form of a stress wave emanating from its tip while the direction of the microcrack propagation depends also on the orientations of planes of low cohesive strength. Assume that the thermodynamic state of the specimen at the onset of propagation is in equilibrium and defined by the manifold $\left\{\overline{e},\overline{D},\overline{T}\right\}_{\overline{s}}$ where the bar over symbol stands for average. Crack propagation is a non-stationary and dissipative process that may be either stable or unstable. In the latter case specimen will fracture. When the propagation of microcrack terminates at state $\left\{\overline{e}+D\overline{e},\overline{D}+D\overline{D},\overline{T}+D\overline{T}\right\}_{\overline{s}}$ the process is stable. The proximity between two states may be "small" or "large". In the first case the methods of thermodynamic with internal variables apply which not true in the case of large "distance" between sequent equilibrium states. Thus, the estimate of the proximity between sequent equilibrium states is of significant importance.

To illustrate the concepts of modern statistical physics consider a sub-volume (SB), of size L^d and known texture disorder, that is small enough to consider macroscopic stresses and strain to be homogeneous but large enough to be statistically homogeneous. The macroscopic deformation is viewed as a temporal sequence of states equilibrated by the thermodynamic affinity $\overline{A}_i=\overline{J}_i-\overline{R}_i\leq 0$ that are separated by segments of non-stationary states during which the released energy is distributed to the material until the principle of minimum of strain energy is satisfied. The "length" of this segment depends on the number of microcracks that commence propagation at a same magnitude of external action (either $\overline{s}$ or $\overline{e}$). Applying the concept of avalanche order (Maslov, 1995), defined as the number of microcracks commence propagation, the proximity of equilibrated states in simulations and acoustic emission tests can be measured. The presence of avalanches of large orders is characteristic of a process of far-form-equilibrium (FFE) type, in which that the potential and attractor-state do not exist and the process depends on the fluctuations of fields (Nicolis and Prigogine, 1977). Preponderance of order one avalanches indicates close-to-equilibrium (CTE) process within the potential exists and is defined by the minimum of the entropy production. A CTE process is driven by averages of fields.

In tests on a representative statistical sample of specimens that are “identical” on macro scale but different on micro scale the scatter of data in CTE processes are small and distribution normally about averages. The contrast is true in FFE processes.

An FFE process consists of two sub-processes. During the initial of hardening phase of deformation of SB damage evolves by random site microcrack nucleation at week spots and all avalanche are of order one. The material is statistically homogeneous on the scale on the sub-volume and deterministic continuum damage mechanics is applicable since all macroscopic parameters depend on damage density. Within the latter part of the hardening phase the accumulate damage is sufficiently large to increase the probabilities of finding a weak spot next to a microcrack or two microcracks close enough to affect local released energy. Hence, the effect of microcrack propagation on the specimen parameters and avalanche order increases as well. Appearance of the damage clusters defined as interacting or contiguous microcracks, is a result of the transition in the mode of the damage evolution. Effective parameters of the SB scale as L^d, i.e. by the Euclid dimension d of SB.

As the length of largest cluster of contiguous (macrocrack) or interacting (shear band), x, or correlation length, becomes equal to L the SB cannot transfer the stresses at least in one direction rendering the SB to be statistically heterogeneous. In the ensuing phase, $x > L$, SB softens in the direction in which the momentum cannot be transferred. Hence, the SB becomes a larger defect of the size of SB, which can be either a microcrack or shear band, and the stress that cannot be transferred is distributed to neighboring SBs.

The local stresses and strains are fractal in the hardening phase and multifractal in the softening phase. Multifractality of local stresses, strains and damage makes possible to estimate analytically the probability of a finding a very large local stress (or local J-integral) which otherwise requires a large number of simulations or tests. The magnitudes of local stresses are defined analytically by statistical moments of their magnitudes.

Summary of Statistical Damage Mechanics

The sharp change of the research in damage mechanics is necessary to introduce the effect of material texture on the damage evolution and provide means to estimate the proximity and mode of failure, measurable order parameter (correlation length ?), define the damage tolerance and damage detection periods. Proposed direction of research will provide the essential design tool needed to estimate the mode and onsets of fatigue failure, residual strength of damaged structures, durability, damage tolerance, effect of corrosion on structural failure and schedule NDI damage detection periods. Generalizations to the dynamic, thermal and chemical processes is possible once the physics and statistical foundation is put together into a large numerical code.

Requirements

Work on this research takes several different talents and knowledge such as statistics, statistical physics, and definitions of material disorder, computational mechanics and parallel computation. Bridging of the scales is the part and parcel of this method that seamlessly changes from one scale to other by changes of the resolution length according to the selected volume and sub-volume. At each step from atomic to structure scale all effective parameters and local fluctuations of random variables and their effect on macroscopic deformation, mode and onset of structural failure are defined as a function of the considered size using the scaling laws similar to those of percolation theory. Determination of universal scaling exponents, who must satisfy all Kadanoff criteria, of the considered universal group takes skill, experience, many simulations and large parallel code and computer. Once this is done the scales are bridged using a re-tooled renormalization group transformation method.

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Dynamics of Solids and Structures

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Introduction

Dynamic mathematical models and experimental characterization of dynamic phenomena are pervasive throughout solid mechanics and indeed fluid mechanics, physics and chemistry. But not yet biology. The latter presents a large challenge and a great opportunity.

In recent summaries of research trends and directions in solid [1] and computational [2] mechanics, dynamics is always implicit and sometimes explicit in many of the topics discussed there.

Over the last two decades much of the excitement in dynamics has centered on non-linear dynamics and chaos of low dimensional systems [3]. This interest extends throughout science and engineering and the mechanics community has contributed a number of the earliest and most important concepts and results. In recent years many researchers have turned their attention to complexity, the non-linear dynamics of very high dimensional systems. A recent treatment of relevant ideas in fluid-structure interaction is available [4]. And a forthcoming congress [5] deals with these issues over a broad range of mechanics phenomena.

A second major stream of advance in dynamics over the last few decades has been in wave propagation in solids, with particular interest in not only metals but also in plastic and biological materials with or without inclusions such as cracks and cavities.

In each of these areas we have identified the most exciting questions and possibilities for future research. These are listed in Tables 5.1 (Wave Propagation in Solids) and 5.2 (Dynamics of Structures and Machines). In these tables, the connections to other themes of this workshop are indicated (in parentheses) in a representative, but not exhaustive way.

What is New?

As suggested in table 5.1 (Wave Propagation in Solids), new nano and MEMS sensors are emerging for ultrasonic wave propagation measurements. These developments provide valuable synergy in that these sensors will advance our understanding of wave phenomena and, in turn, wave measurement goals will provide an incentive and impetus for sensor development. Multi-scale material characterization is one important advance that will be made possible by this new capability and significant progress in our understanding of non-destructive evaluation, constitutive behavior at high-strain rates, kinetics of phase transformation, frictional laws at high-speed sliding surfaces for both homogenous and heterogenous materials is to be expected.

As indicated in Table 5.2 (Dynamics of Structures and Machines), to better understand and improve the performance of modern structures and machines, advances in dynamic modeling are needed and are being made. Improved characterization of friction, impact and damping are keys to these advances. System identification (ID) methods are needed for both nonlinear and linear systems of high complexity. Yet if complex system models are to be useful to advance understanding and support creative and timely design, a reduction in the complexity (or numbers of degrees of freedom) must be often made while retaining the accuracy of the original dynamical model. By enabling a much reduced size (or order) and thus computational cost, reduced order models are and will be a key enabling methodology for many dynamical systems.

These reduced order models often invoke a global model representation (for both nonlinear and linear systems) rather than a local model such as finite elements. Note, however that the global modes themselves are usually obtained from a finite element model. If the number of modes in a frequency bandwidth is very large, an asymptotic theory may be developed that is independent of modal details. On the other hand if the number of modes is small, classical modal methods apply. As usual, the intermediate case of many, but not very many, modes has proven most difficult and remains an open question.

Beyond advances in modeling methodologies per se, (1) we anticipate the advent of nano and MEMS dynamical structures and devices, (2) the desire and capability for active control of (smart) structures, (3) the desire and capability for condition based ("health") monitoring and (4) the increasing realization that even within classical (as distinct from quantum) mechanics, there is a sensitivity to initial conditions and the ever present possibility of chaos in complex, nonlinear systems. All these expected advances raise the pervasive question of predictability vs. non-predictability in many dynamical models. While gross features may be repeatable and predictable, that will not always be true with respect to details that may be important for some applications. And hence ever more refined models to smaller and smaller scales may not always be necessary or desirable. Rather we must face the issue of modeling and design in the face of uncertainty.

Grand Challenges of Dynamics of Solids and Structures

So what are some of the grand challenges where the best way forward is not yet clear? Here a few representative examples that capture some of the excitement and promise for the future.

- Establish fundamental and well-founded relations between a material condition as measured non-destructively and the ultimate strength of a solid or structure as measured destructively.

- Develop (theoretical or experimental) techniques to determine the "minimally essential" (smallest number of states or degrees of freedom) model from a set of numerical tests or physical measurements for the representation of nonlinear, complex dynamical systems to a desired level of accuracy.
- Develop effective mathematical methods and experimental procedures to determine the essence of dynamic behavior and wave propagation in the presence of uncertainty.

Dynamics of solids and structures is a subject rich with history, promise and potential. In this brief account a prospectus has been offered to help realize that promise and potential.

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Tables 5.1

- wave propagation in solids
- development of nanosensors and mems for ultrasonic measurement (nano technology, active materials)
- techniques for multi-scale materials characterization (fracture and fatigue, damage mechanics)
- measurement models for nde (damage mechanics)
- techniques for detection of anomalies, e.g. inclusions and cracks (damage mechanics, fracture and fatigue)
- constitutive behavior at high strain rates (plasticity, materials processing)
- kinetics of phase transformation (damage mechanics, active materials)
- frictional laws at high speed interfaces(fracture and fatigue)
- failure of heterogenous solids (design of materials)
- high-speed, high resolution diagnostic methods in visible and infrared regimes (experimental mechanics)

Tables 5.2

- dynamics of structures and machines
- modeling
- friction & impact (tribology and contact)
- damping (active materials)
- systems identification (experimental mechanics)
- model reduction (computational mechanics)

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- mid-frequency range (complexity)
- multi-body dynamics (biomechanics)
- nano/mems structures and devices
- active control of structures and devices (active materials)
- localization
- mems
- conditioned based monitoring (nano sensors, “health” monitoring)
- predictability vs. non-predictability in complex, high-degree-of-freedom, nonlinear systems (all)

Experimental Mechanics

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The contribution of Mechanics to engineering has historically been a synergistic interaction of experiment and analysis. Experiments have either discovered new phenomena or analyses have discovered discrepancies or predictions based on the frame work of past observations. Inasmuch as we live in a physical world, which we wish to harness for man's betterment, we are bound to physical observation as the basis of building our living environment.

In the mechanics community the last few decades have seen an unhealthy shift in emphasis to analysis at the expense of experiment. One indicator is the number of papers published in the mechanics journals as illustrated in figure 1: Counting any paper containing reference to experimental data[1], shows the distinct decline of experimental discovery in the past decades. Similarly, the number of experimentally oriented investigators at universities has declined to a ratio of one in 6 or 7 having analytical interests. This compares with a reverse ratio of about 3 or 4 experimentalists for every theoretician in Physics and a still larger ratio in Chemistry and Biology where experiments are clearly dominant. A continuing trend for mechanics spells trouble because a further, gradual decrease of physical data for an increasing pool of analysts will eventually provide nothing to analyze: Mechanics will become simply a service discipline attached to other sciences that interface with engineering.

This imbalance is particularly troublesome because a reversal of the current trend cannot be commanded immediately and a continuing lack of attention to the imbalance provokes thus a manpower instability: Fewer experimentalists — with the characteristically longer time constant for experimental work and learning — generates proportionately fewer of its kind. Though it may be possible to entice analysts to devote efforts to experiments, history demonstrates this corrective process not to be significant. Bearing in mind further the long time constant of academic training to replenish the pool of researchers devoted to the skills of experimental investigations, it appears high time that some guided correction to the situation be initiated at the funding agencies.

With new technologies arriving on the scene that await contributions from the mechanics community — *e.g.* micro- and nano-mechanics — the time appears right that a concerted effort be made nationally to provide a larger and more powerful pool of experimentally oriented investigators. Tremendous needs exist in developing new investigative methods and instrumentation to deal with new technological territory. Mistakes will be made, and the process may be slow. But without such a reorientation the modeling information needed for mechanics problems will not become available. While many in the mechanics community have seen and responded to needs in other disciplines such as electronic packaging and materials science, these other disciplines are, on the whole, interested in different phenomena and are unlikely to be directed towards those applications typically provided to and by engineering through the discipline of mechanics.

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[1] regardless of whether the data are a major or only "quoted" part of the presentation

Mechanics of Material Processing

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There have been numerous important advances in the area of materials processing over the past two decades. In this summary paper, we will focus on the areas classified as material removal processes such as machining, grinding and polishing. However, we do not restrict ourselves to conventional machining by "chip" removal processes, but rather broaden our view to include other material removal mechanisms such as lasers and chemo-mechanical processes.

Material removal processes have tremendous economic importance. For example, according to Dr. Eugene Merchant, mechanical machining operations alone account for 15% of the value of all components manufactured worldwide. However, scientific understanding and ability to predict the behavior of these processes remains poor, and many of the issues that limit this understanding relate to lack of information about the fundamental mechanical behavior of the processes. An excellent historical review of progress in conventional machining and grinding processes can be found in a special issue of *Applied Mechanics Reviews* entitled "US Machining and Grinding research in the 20th Century" [1].

As suggested in the workshop instructions, we have divided this discussion paper into three sections. The first discusses the most exciting and interesting results and changes that have occurred in material removal processes in the past two decades. The second section attempts to identify unresolved issues pertaining to these developments. The third section takes a view toward the future of material removal processes.

Exciting Results and Changes in Material Removal Processes

There have been substantial changes in material removal processes over the past two decades. Some of the most substantial changes (of which we are aware) have been in the following areas:

- High-speed Machining,
- Novel Machine Tool Designs/Parallel Actuator Systems,
- Micromachining & Manufacture of Meso-scale Components,
- Laser-Assisted Machining,
- High-speed Grinding,
- Electronics Processing Techniques/Chemical-Mechanical Planarization.

Selected items are discussed below in greater detail.

High-Speed Machining

Over the past 15 years, there has been the rapid successful commercialization of reliable *high-speed machining systems*. The components that have enabled the development of high-speed machining include: (1) spindles capable of speeds exceeding 40 thousand revolutions per minute while simultaneously delivering tens of kilowatts of power to the cutting zone; (2) rigid, low-mass machine-tool structures; (3) high-speed linear slide-ways capable of coordinated linear motions at tangential speeds of up to 0.6 meters per second and accelerations of 20 meters per second squared. Machines that are designed to take advantage of these components are capable of metal removal rates that are greater than ten times those of their conventional counterparts.

The most dramatic applications of high-speed machining have been in the manufacture of aluminum components; volumetric material removal rates can be extremely high, often thousands of cubic centimeters per minute. Application of this technology began in the aerospace industry. High-speed machining is changing the way aircraft are manufactured by enabling the replacement of sheet-metal assemblies with machined monolithic components, resulting in substantial cost savings and improved performance. These same ideas are now spreading into the much higher volume communications industry, where they are being implemented in the manufacture of electronics chassis. A major challenge for researchers in applied mechanics is to develop reliable models of high-speed machining processes that couple the plastic deformations occurring at the tool-chip interface with the static and dynamic deflections of the machine-tool structure. This is necessary to supplement or replace standard empirical databases such as the *Machining Data Handbook*, which were expensive to produce and have not kept pace with the development of high-speed machines.

Novel Machine Tool Structure and Actuator Designs

Traditional machining systems have consisted of serially-coupled, stacked components, each capable of linear or rotary motion with one degree-of-freedom. Typically, linear axes have been driven by rotary actuators coupled by high-force-gain lead-screws, ball-screws and rack-and-pinion drives. Research on the design of such drive systems has enabled their use in high-speed machining centers, producing feed rates of up to 1 m/s with accelerations of 1 g. For a small work volume, the acceleration of the machine tool axes is more important than the maximum speed in determining the ultimate time it takes to manufacture a component. To address this issue, some machine-tool manufacturers have begun to explore *linear motors* as an alternative drive system for high-speed machines. These systems are capable of more than twice the maximum speeds and accelerations of mechanical drives. However, they also have a number of disadvantages: (1) low force amplification factors make them more sensitive to cutting forces and changes in the inertia of the machine-tool structure that may occur as axis orientations change and workpiece mass is added or removed; (2) because they require strong permanent magnets, ferrous machining chips may collect on the motor housings; (3) they generate a large amount of heat, thereby making a substantial (and often dominant) contribution to the thermal errors of the system. However, improvements in accelerations and speeds are so attractive that they motivate manufactures to attempt to find solutions to these problems rather than abandon the technology.

Another innovative design idea for high-speed machines is the development of parallel architecture machine-tool structures. From the perspective of high-speed machining, the development of the new machines addresses a major disadvantage of serial construction: the necessity for some axes to carry the additional mass with other axes and their actuators. Parallel machines are made possible by the development of powerful CNC controllers able to account for geometric complexity in the controller software. These systems can use traditional ballscrew drives or linear motor systems as actuators. Ideally, this type of machine can be stiffer, have lower mass and higher accelerations, and be more accurate than conventional designs. However, these advantages have not yet been realized in practice due to a number of disadvantages including: (1) parasitic bending of the struts due to imperfect joints (friction, play etc.); (2) magnification of thermally induced errors due to strut length; (3) difficulty in obtaining direct position feedback along the struts and in determining the locations of the axes of rotation for each joint; (4) variation in system kinematics, statics, and dynamics within the work volume.

Tlusty has recently argued that many of the advantages of these parallel machines may be overstated and are not practically realizable. Despite these formidable challenges, work on parallel machines continues with the final verdict on comparison with conventional construction as yet unknown. Certainly, the new designs are competing with years (perhaps centuries) of experience using conventional constructions, and therefore prediction of their ultimate performance is difficult.

Micromachining & Manufacture of Meso-Scale Components

There has been substantial recent interest in machining systems capable of generating complex three- dimensional features in a size range between the capabilities of conventional machines and lithographic techniques. Various techniques have been proposed to accomplish this goal, including micro-mechanical machining (plastic deformation), laser micro-machining, and micro-electro-discharge machining (micro-EDM). Applications of such techniques include the manufacture of so-called meso-scale devices for bio-medical, power-generation and military applications. Presently, mechanics-based models of such processes are in their infancy; improved models are required for the development of adequate tools for predicting the dimensional and mechanical integrity of the final parts that are produced.

Chemical-Mechanical Planarization Techniques

As electronic device dimensions decrease, more and more stringent tolerances must be met, until finally the mechanical methods for processing silicon wafers become inadequate. The next generation of electronic devices will employe minimum line-widths of 180 nm. In order to accomplish this and still maintain focus in the lithography systems, the wafer surface must be held to a plane within 18 nm. Chemical-mechanical polishing techniques have been developed to accomplish this, but the basic physical mechanisms for material removal are not well understood.

Key Unresolved Problems

Data on Models for Dynamic Material Deformation and High Rate Effects

Predictive simulations based upon sophisticated numerical methods have the potential to enable optimal choice of process parameters for modern machining operations. However, the state-of-the-art in predictive modeling of machining operations is severely limited by insufficient measurement capability and materials data. In other words, current models give impressive qualitative results, but data to validate these results is nearly nonexistent. Some recent attempts to compare results of simulations with experiments on deformation processes in which rapid heating occurs indicate that there can be large errors in simulated results, such as predictions of melting of the workpiece material, that do not occur during the actural deformation process. Without an effort to improve the state-of-the-art, industries that are currently receptive to the use of modern numerical simulation techniques may become frustrated with the lack of quantitative accuracy. This effort will advance the state-of-the-art in two areas: (1) fundamental advanced machining metrology and simulation; and (2) measurement of fundamental data on the behavior of materials at high strain, strain rate, and temperature needed for input into simulations of machining.

The impact of this type of modeling is broad ranging. Examples include: (1) the development of techniques for scientific tool designs tailored to minimize wear rates in specific materials; (2) coupling of the dynamics of the plastic flows generated in machining to the behavior of the machine-tool structure, enabling better estimates to be made of machining stability; this problem has proved to be critical for successful implementation of high-speed machining.

Meso-Scale Material Behavior

With the rapid development of non-lithographic manufacturing processes such as laser machining and micro-mechanical machining to manufacture smaller and smaller features, inhomogeneities in the material due to grain structure become increasingly important for understanding and predicting behavior. This requires the development of meso-scale modeling techniques that account for grain structure and orientation. Such techniques would also be useful in generating improved physics-based models of the dynamic behavior of materials for simulations of more conventional larger scale machining operations.

“Design” of Machine Dynamics, Ensuring Dynamic Repeatability

The importance of dynamic stability in high-speed machining has highlighted the need for designs of machine components that produce repeatable dynamic behavior. Predicting the dynamics is difficult primarily due to the lack of good models of the mechanical behavior of interfaces between machine components, particularly with regard to the effect of these interfaces on the damping of machine components and structures.

Environmentally-Friendly Processing – “Green” Machining

Pressure to develop environmentally benign manufacturing operations has driven manufacturers to examine the reduction or elimination of machining coolants and lubricants. However, the effect of these substances on the fundamental behavior of the machine operations is not well understood and this lack of understanding inhibits the development of optimally “green” machining systems. Pressure on U.S. manufacturers will grow rapidly as foreign competitors who have made progress in environmentally friendly manufacturing methods (particularly in Europe and Japan) begin to adopt trade standards that U.S. companies are unable to meet.

Residual Stress Prediction and Control

High-speed machining has enabled an increase to occur in the types of components can be machined. However, there are many more improvements that can still be made. For example, large thin-walled components are currently being manufactured for the aerospace, communication, ship building and space industries that are subject to substantial deformation due to residual and machining-induced stresses. Internal studies at Boeing have indicated that the cost of scrapping parts associated with unpredictable residual stresses can amount to many millions of dollars per year. Furthermore, the desire to reduce the “chip tax” associated with recycling material from high-speed machining has driven manufacturers to consider near-net-shape processes that can be used in conjunction with high-speed machining. These processes can add even greater complexity and variation in the stresses that are present in the initial workpiece.

New Ideas Applications or Technologies

There are many areas in manufacturing that show potential for growth in the next decade. Some of these areas have not traditionally been covered by manufacturing and mechanical engineering. Examples include:

- Electronics Manufacturing and Precision Engineering
- Manufacture of biomedical devices
  - Micro-surgical robotics
  - Tissue-engineered devices
- Solid Freeform Fabrication (e.g., laser sintering)

Funding for such areas may also come from sources not traditionally associated with mechanical engineering, including the National Institutes of Health and consortia such as SEMATECH in the electronics industry.

LVIII

Research Needs in Computational Mechanics

Ted Belytschko
Northwestern University

The purpose of this paper is to examine directions for future research in computational mechanics that are relevant to broad national goals. For this purpose, we will first review the major issues that are driving computational mechanics and the barriers to computability. I will focus on nonlinear simulation, for it is the most interesting and profitable area for research. It is argued that the barriers to computability correspond to the issues in which research progress is critical. The reader is also urged to read the NRC report "Research Direction in Computational Mechanics."

The major application of computational mechanics in the industry are in

1. prototype simulation
2. process simulation
3. design of new materials

Prototype simulation refers to the evaluation of new designs by simulation of computer models instead of tests. Examples are crashworthiness simulation of automobiles; drop tests on products such as cellphones, televisions, chain saws and other products; simulation of extreme events in various facilities, such as seismic response of bridges, buildings and manufacturing facilities; weapons effects on structures and military vehicles, etc. In order to speed design cycles, reduce design costs, and improve safety, replacement of tests by simulation is a necessity.

Process simulation refers to the simulations of manufacturing process, such as sheet metal forming, extrusion, wafer manufacturing and many others. Again, there is a need to replace tests of prototypes by simulation to speed design times and reduce costs.

The design of new materials is the holy grail of material science. The objective is to be able to perform the initial design of new materials on the basis of computer simulations. Properties such as ductility, post-yield behavior, fracture toughness, and many other properties of a material need to be predicted on the basis of fundamental laws. This often entails simulations combining quantum mechanics, molecular mechanics and continuum mechanics, either on a hierarchical or strongly couple manner.

All of the above involve nonlinear simulation, yet most are not achievable with any reasonable robustness and fidelity today because of shortcomings in our understanding of mechanics and our computational capabilities.

To highlight the major difficulties in computability, we list in Table 1 the major barriers to computability in solid and structural mechanics as taken from Belytschko and Mish (2001).

Table 1. Weights for factors contributing to levels of difficulty

Factor	Property	Physical attributes
W_1	Smoothness	Contact-impact and cracking
W_2	Geometric stability	Buckling, limit points-imperfection sensitivity
W_3	Material stability	Shear bands, cracking, and damage
W_4	Effectiveness of constitutive equations	Ability of constitutive equations to replicate load paths-deteriorates significantly for cyclic loads
W_5	Variability in data	Stochastic and epistemic uncertainties in loads, material properties, initial conditions, boundary conditions and geometry.
W_6	Resolution requirements	Driven by ratio of fine scale to coarse scale response

Each of the above areas still requires significant work to provide robust, effective numerical methods. Particularly important in prototype simulation are the problems of material stability: how to transition from an intact material to a crack, how to effectively represent a crack in a computational model. Some new methods have recently been developed in Belytschko et al (2001), but they deal primarily with crack modeling: the issue of constitutive laws that accurately predict crack formation is still an open issue. Damage models such as described by Krajcinovic and Mastilovic (1995) are a promising approach.

The issue of uncertainties also can not be dealt with effectively at this time. Much of the work on probabilistic methods is not relevant to applications in nonlinear simulation, for it focuses on the extreme events. What is needed are methods that provide some guidance as to the range of expected results and provide computationally inexpensive ways to judge the effects of roughness and instabilities on uncertainties in the response. Promising avenues are anti-optimization, Elishakoff et al (1994) and sensitivity methods (see Tsay and Arora (1990)), although the latter may not be too useful in the non-smooth, unstable problems that permeate nonlinear simulation.

Resolution requirements are also a major barrier to computability. The U.S. research posture seems to rely on Moore’s law to eliminate these difficulties. Moore’s law states computer power increases by a factor of two every eighteen months (there are variants ranging from 12 months to 24 months) and it has enabled rapid increases in resolution when problems were primarily two dimensional over the past three decades. However, as engineers rely increasingly on three dimensional analyses, the benefits of Moore’s law become less dramatic. For a three dimensional explicit calculation of a hyperbolic partial differential equation, the computations required for a simulation for a mesh with elements along each side is of order. Over the next decade, Moore’s law predicts that computer power will increase by 100. Yet the consequent increase in the numbers of elements along an edge of a three dimensional calculation is only 3.2, so that we can not expect even an order of magnitude increase in resolution in the next decade due to Moore’s law.

Some of the major developments of the past decade have been driven by the need to accommodate resolution requirements effectively: examples are adaptive methods, Oden et al (1989) and multiscale methods (Hughes et al (1998)). In the latter, fine scale features are resolved in coarse scale models by introducing their effect through variational means. Another promising avenue for combining different scales are partition of unity methods, Babuska and Melenck (1997) and meshfree methods (Belytschko et al (1994)). Methods for combining models ranging from quantum mechanics to continuum models are reviewed by Rudd and

Broughton (2000), an example is Abraham et al (1998). The latter are particularly important in the design of materials, since the ultimate goal of this effort is to predict the properties of new materials, including fracture properties, by simulation.

Thus the major challenges in computational mechanics appear to be:

1. dealing with problems which are not smooth or stable with uncertainties
2. methods for multiscale phenomena, including coupling to molecular and quantum mechanics; both adaptive methods and embedding methods, such as partition of unity methods, are promising avenues
3. development of methods for computational determination of constitutive properties—this involves many tasks, including linking determination of nonlinear properties from microscale models, many issues in mechanics

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Brazilian Spatial Agency, Agência Espacial Brasileira (AEB)

Professor Luiz Bevilacqua is the new president of the Brazilian Spatial Agency, Agência Espacial Brasileira (AEB).

Professor Bevilacqua is one of the founders of ABCM, the Brazilian Society of Mechanical Sciences. He earned a Ph.D. in Applied Mechanics from Stanford University. At present, he is coordinating the graduation course of LNCC, National Laboratory of Scientific Computation. In his professional life he has occupied very important positions, such as the General Secretary of the Minister of Science and Technology, and Director of the two most important agencies for scientific founding, CAPES and CNPq. He is the author of two books and has published many papers.

Correction

In the previous issue of *Mechanics* (Volume 32, Number 5-6), the minutes of the 65th Meeting of the Board of Directors was incorrectly published in abbreviated and unofficial form. The official minutes will appear in the next issue.

Letter from the Secretary of the Fellows

Dear Fellows of the American Academy of Mechanics:

I am writing you to formally invite nominations for the grade of Fellow of AAM. A nomination form is enclosed for your use. Also, an updated list of Fellows is available on the AAM website. I am sending this invitation early to allow more time for nominations.

The following new Fellows were elected at the November 2002 meeting of the Fellows in New Orleans: Professors Robert Brodkey, Giulio Maier, Robert McMeeking, and Dr. Ken Chong.

If you wish to nominate more than one colleague, you may make copies of the nomination form. Each nomination form should be completed and signed by two fellows, and a two-page resume of the nominee must accompany the nomination. Nominations for a Fellow of AAM must be received in my office by September 22, 2003. All nominees will be placed on a ballot in the order they are received. The ballots will be mailed to you for your vote in September. The ballots will be counted at the meeting of Fellows at the ASME IMECE in Washington, DC. Hopefully, the date, place, and time of the meeting will be in the Committee Meeting booklet available at the Congress.

I will look forward to seeing you in Washington, DC, in November.

Sincerely yours,

Subhendu K. Datta
Secretary of the Fellows
Chair, Department of Mechanical Engineering
University of Colorado, UCB 427
Boulder, CO 80309-0427
Tel.: (303) 492-0287; Fax: (303) 492-3498; e-mail: dattas@spot.colorado.edu

NOMINATION FOR FELLOW OF THE AMERICAN ACADEMY OF MECHANICS

NOTES:

- *Persons nominated must be members of the Academy* (Bylaws, III 1)
- *Nominations must be made by* **two** *of the Fellows* (Bylaws, III 2)
- *Fellows shall be elected on the basis of their contributions to mechanics* (Bylaws, III 1)

Name of the member nominated (*please print*)

____

Citation (*please state in no more than* **fifteen words** *the basis of the nomination*)

____

____

____

Nominated by (*signature of two fellows required***)**

Signature: ____

Printed Name: ______________________________ **Date:** ________________

Signature: ____

Printed Name: ______________________________ **Date:** ________________

Please mail this nomination form (no faxes please!) to:

Professor Subhendu K. Datta, Chair
Department of Mechanical Engineering
University of Colorado
UCB 427
Boulder, CO 80309-0427, USA

so as to reach him on or before **September 22, 2003.** The nomination should include one good copy of a **two-page resume** of the member nominated.

AAM AWARDS NOMINATION

The Awards Committee of the American Academy of Mechanics requests nominations for the following two awards to be presented at the forthcoming ASME International Mechanical Engineering Congress and Exposition in Washington, November 15-21, 2003.

The 2003 American Academy of Mechanics Distinguished Service Award

This award is presented in recognition of a lifetime of distinguished service in the field of Theoretical and Applied Mechanics and to the Academy. Preliminary nominations should consist of a one-page letter describing the outstanding service of the nominee, plus a one-page biographical sketch, and the names of at least three people willing to write letters of support in the event that the Awards Committee requests them.

The 2003 American Academy of Mechanics Junior Achievement Award

This award is presented in recognition of outstanding research in the field of Theoretical and Applied Mechanics by a junior investigator. The nominee's highest degree must have been received after December 31, 1992. Preliminary nominations should consist of a one-page letter describing the research of the nominee, plus a one-page biographical sketch and copies of at least three publications of the nominee.

Note: *Preliminary nominations for both awards, postmarked by August 1, 2003, should be sent to Stephen H. Crandall at crandall@mit.edu. Once the preliminary materials have been reviewed, additional information may be requested from the nominators.*

2003 AAM Awards Committee

S. H. Crandall: *Chair*, J. T. Oden, W. G. Knauss, R. C. Batra, C. E. Taylor

American Academy of Mechanics

Founders Prize and Grant

Up to $10,000 For the Academic Year 2003-2004
(Deadline: July 1, 2003)

The American Academy of Mechanics is pleased to announce the availability of a Founder's Prize and Grant to be awarded in September 2003 to a doctoral candidate in the field of Mechanics. Funding has been arranged by the Robert M. and Mary Haythornthwaite Foundation through the good offices of Professor Haythornthwaite, founder and first President of the Academy. The aware will be made on the recommendation of an AAM committee. The prize consists of a Certificate and $1,000 that will be presented at the annual meeting of the Academy, usually held in November. The Grant will be made to that same person in two installments, $6,000 in September 2003 and up to $3,000 in January 2004, the latter dependent on the size of the approved budget and receipt by the AAM committee of an acceptable progress report. In order to encourage contestants to think constructively about the impact of new and pending developments, they will be asked to compose an original essay of no more than a thousand words under the title "Progress through Mechanics". The winning essay will be published in *mechanics*. The award is open to those who, as of July 1, 2003, are registered as graduate students at a degree granting institution within the Americas, have completed at least one year of full-time graduate study at that institution, have been assigned a thesis advisor at the institution and have had a doctoral thesis topic emphasizing mechanics approved by the institution following candidacy or equivalent procedures. There are no restrictions with regard to citizenship, residency, race, religion, or sex. Letters of support will be required of the thesis advisor and in addition one from either a Member or a Fellow of AAM. Contestants will be judged on the basis of the essay, plans, references and academic history. The intent of the Grant is to support the research of the student through an approved combination of equipment purchases, information access, travel, etc., but not routine living expenses or fees. Detailed rules for the competition will be issued soon: to receive them, express your interest to the committee by FAX to (215) 204-6936, or by writing to:

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International Congress of Theoretical and Applied Mechanics

August 15 - 21, 2004 ¨ Warsaw, Poland

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First Announcement and Call For Papers

http://ictam04.ippt.gov.pl

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Congress participants are encouraged to submit a paper. Papers are sought for all topics corresponding to Pre-Nominated Session or Mini-Symposium subject matters. The paper must be in English and should present material that is novel and preferably unpublished at the time of the Congress. All papers presented at the Congress are by invitation based on the recommendation of the International Papers Committee. No author will be invited to present more than one paper. Prospective authors are asked to submit only one paper for consideration.

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Smart materials and structures ? Tissue, cellular and molecular biomechanics ? Mechanics of thin films and nanostructures ? Microfluidics ? Microgravity flow phenomena ? Atmosphere and ocean dynamics

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Correspondence related to the Congress should be sent to:

Prof. Tomasz Kowalewski, ICTAM04 Secretary-General
Institute of Fundamental Technological Research
Swietokrzyska 21, 00-049 Warszawa, Poland
e-mail: ictam04@ippt.gov.pl

CALL FOR PROPOSALS TO HOST AN IUTAM SYMPOSIUM or INSTRUCTIONAL SUMMER SCHOOL

in 2006 or 2007

The United States National Committee on Theoretical and Applied Mechanics (USNC/TAM) seeks proposals from U. S. authors and institutions to host IUTAM Symposia or Instructional Summer Schools in 2006 or 2007. Information for proposals from the United States can be found on the USNC/TAM website at: http://www7.nationalacademies.org/usnctam. IUTAM provides a small amount of financial support for symposia and summer schools. US organizers are strongly encouraged to seek additional financial support from other sources. The primary use of financial support is to help with travel expenses for younger scientists and for scientists from developing countries.

IUTAM Symposia

The goal of an IUTAM Symposium is to assemble a group of active scientists, within a well-defined field, for the development of science in that field. Participation is by invitation only. In order to achieve effective communication within the group it should, typically, be limited to 60-80 scientists with expertise in the subject area of the symposium. Symposia typically consist of a few invited lectures, and a larger number of contributed papers, presented as lectures and/or posters, all pre-screened by the Symposium Scientific Committee.

IUTAM Instructional Summer Schools

The purpose of an IUTAM Instructional Summer School is to provide lectures by leading experts in a new or emerging field of science and engineering in order to foster developments in that field. Schools are typically 3–5 days in length and intended primarily for younger scientists and those with only limited knowledge in the specific field of the school. Participation of is by invitation only.

Proposal Submission

Proposals from the United States to host a symposium or summer school should be submitted on the appropriate two-page Proposal Submission Form available on the USNC/TAM website. The completed proposal should be sent electronically to the USNC/TAM Secretary (herak@virginia.edu) no later than January 15, 2004. Proposers may submit their proposals directly to IUTAM. However, experience has shown that proposals benefit from the feedback provided by USNC/TAM, and that the recommendation of USNC/TAM when the proposal is finally submitted to IUTAM carries considerable weight.

Final Approvals

Proposals will be assessed by the USNC/TAM and then forwarded to IUTAM where they are reviewed by IUTAM panels. The IUTAM General Assembly will vote on the panel recommendations in August 2004 at the International Congress on Theoretical and Applied Mechanics in Warsaw, Poland (http://ictam04.ippt.gov.pl/).

PACAM VIII

Eighth Pan American Congress of Applied Mechanics

January 5-9, 2004
Havana, Cuba

http://www.pacam8.mcgill.ca/

The Eighth Pan American Congress of Applied Mechanics (PACAM VIII), jointly sponsored by the University of Havana, the Institute of Cybernetics, Mathematics, and Physics of Cuba, and the American Academy of Mechanics, will be held January 5-9, 2004 at the Convention Center, Havana, Cuba. The Honorary Chairman of the Organizing Committee is Prof. Alina Ruiz Jhones of the University of Havana. The Co-Chairmen are Prof. Martin Ostoja-Starzewski of McGill University and Prof. Reinaldo Rodríguez-Ramos of the University of Havana. The Chairman of the Editorial Committee is Prof. Julián Bravo-Castillero of the University of Havana, and the Chairman of the Local Arrangements Committee is Prof. Raúl Guinovart-Diaz of the University of Havana, Cuba.

The aim of sponsors is to promote progress in the broad field of mechanics by (1) exposing engineers and scientists, including graduate students, to new research findings, techniques, and problems, and (2) providing opportunities for personal interactions between mechanicians of North and South America, as well as other continents. It is the only conference sponsored by the American Academy of Mechanics (AAM).

The Pan American Congresses of Applied Mechanics are held every two years early in January, always in a Latin American venue, at a time when few other conferences are scheduled. The previous Congresses were held in Rio de Janeiro, Brazil in 1989; Valparaiso, Chile in 1991; São Paulo, Brazil in 1993; Buenos Aires, Argentina in 1995; San Juan, Puerto Rico in 1997, Rio de Janeiro, Brazil in 1999 and Temuco, Chile in 2002. Participants come from the Americas as well as Africa, Asia, Australia, and Europe.

Persons willing to organize special sessions in any area of mechanics are welcome to contact the organizers listed below. All the future announcements will be made at the website listed above, and through the AAM (http://www.AAMech.org/). Four-page papers for the conference proceedings will be due June 30, 2003, at either address:

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Note on travel to Cuba from the United States-a link has been provided on the PACAM website that shows travel **is** possible to Cuba from the United States.

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1071	Recent development of fluid-structure interaction capabilities in the adina system	Zhang H. Zhang XL. Ji SH. Guo YH. Ledezma G. Elabbasi N. deCougny H.
1087	Nonlinear weighted residual approach: application to laminated beams	Zielinski AP. Frey F.
1099	Hybrid neural network/finite element modelling of wave propagation in infinite domains	Ziemianski L.

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1111	Advanced computational models and techniques in dynamics	Ibrahimbegovic A.
1113	Non-linear dynamics of flexible multibody systems	Ibrahimbegovic A. Taylor RL. Lim H.
1133	Estimation of discretization errors in dynamics	Ladeveze P. Pelle JP.
1149	Structural system identification: from reality to models	Alvin KF. Robertson AN. Reich GW. Park KC.
1177	A delay damage mesomodel of laminates under dynamic loading: basic aspects and identification issues	Allix O. Feissel P. Thevenet P.
1193	Dynamics and time-stepping schemes for elastic shells undergoing finite rotations	Brank B. Korelc J. Ibrahimbegovic A.
1211	An algorithm to solve transient structural non-linear problems for non-matching time-space domains	Combescure A. Gravouil A. Herry B.
1223	Efficient approaches to finite element analysis in earthquake engineering	Davenne L. Ragueneau F. Mazars J. Ibrahimbegovic A.
1241	On the probabilistic-deterministic transition involved in a fragmentation process of brittle materials	Hild F. Denoual C. Forquin P. Brajer X.
1255	Microscale and mesoscale discrete models for dynamic fracture of structures built of brittle material	Ibrahimbegovic A. Delaplace A.
1267	A multiscale computational method for medium-frequency vibrations of assemblies of heterogeneous plates	Ladeveze P. Blanc L. Rouch P. Blanze C.
1277	Nonlinear galerkin methods for the model reduction of nonlinear dynamical systems	Matthies HG. Meyer M.
1287	Inelastic behavior modelling of concrete in low and high strain rate dynamics	Ragueneau F. Gatuingt F.
1301	Material behaviour characterisation using shpb techniques, tests and.simulations	Zhao H.

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1311	An analytical solution for in-plane free vibration and stability of loaded elliptic arches	Nieh KY. Huang CS. Tseng YP.
1329	Two-axis flexure hinges with axially-collocated and symmetric notches	Lobontiu N. Garcia E.
1343	Stress, strain and energy splittings for anisotropic elastic solids under volumetric constraints	Felippa CA. Onate E.
1359	Impact simulation and full scale crash testing of a low profile concrete work zone barrier	Consolazio GR. Chung JH. Gurley KR.
1375	Active control of beam with magneto strictive layer	Kumar JS. Ganesan N. Swarnamani S. Padmanabhan C.
1383	A numerical technique to predict periodic and quasi-periodic response of nonlinear dynamic systems	Sarkar S. Venkatraman K.
1395	Rigid body mode and spurious mode in the dual boundary element formulation for the laplace problems	Chen JT. Chen WC. Lin SR. Chen IL.
1405	An implicit formulation of the bodner-partom constitutive equations	Andersson H.
1415	Large deflection analyses of skew plates using hybrid/mixed finite element method	Duan M. Mahendran M.

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339	System identification of the vincent thomas suspension bridge using earthquake records	Smyth AW. Pei JS. Masri SF.
369	Large displacement behaviour of a structural model with foundation uplift under impulsive and earthquake excitations	Oliveto G. Calio N. Greco A.
395	Soil-pile-structure interaction under sh wave excitation	Koo KK. Chau KT. Yang X. Lam SS. Wong YL.
417	Evaluation of modal pushover analysis using generic frames	Chintanapakdee C. Chopra AK.
443	Performance of hollow composite members subjected to cyclic eccentric loading	Hsu HL. Liang LL.
463	The seismic performance of braced timber pile bents	Shama AA. Mander JB.
483	Structural vibration control by shape memory alloy damper	Han YL. Li QS. Li AQ. Leung AYT. Lin PH.

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495	Time delayed control of structural systems	Udwadia FE. von Bremen HF. Kumar R. Hosseini M.
537	Experimental and theoretical simulations of seismic poundings between two adjacent structures	Chau KT. Wei XX. Guo X. Shen CY.
555	Asymmetric one-storey elastic systems with non-linear viscous and viscoelastic dampers: earthquake response	Lin WH. Chopra AK.
579	Asymmetric one-storey elastic systems with non-linear viscous and viscoelastic dampers: simplified analysis and supplemental damping system design	Lin WH. Chopra AK.
597	Exact computation of input-energy spectra from fourier amplitude spectra	Ordaz M. Huerta B. Reinoso E.
607	Inelastic dynamic analysis of rc bridges accounting for spatial variability of ground motion, site effects and soil-structure interaction phenomena. part 1: methodology and analytical tools	Sextos AG. Pitilakis KD. Kappos AJ.
629	Inelastic dynamic analysis of rc bridges accounting for spatial variability of ground motion, site effects and soil-structure interaction phenomena. part 2: parametric study	Sextos AG. Kappos AJ. Pitilakis KD.

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653	Scattering of elastic waves by a general anisotropic basin. part 2: a 3d model	Dravinski M.
671	Optimum multiple tuned mass dampers for structures under the ground acceleration based on the uniform distribution of system parameters	Li CX. Liu YX.
691	The effects of torsion and motion coupling in site response estimation	Ghayamghamian MR. Motosaka M.
711	Optimum seismic zoning for multiple types of structures	Garcia-Perez J. Castellanos F. Diaz O.
731	Seismic test of a full-scale model of a five-storey stone pagoda	Kim JK. Ryu H.
751	Reliability-based robust control for uncertain dynamical systems using feedback of incomplete noisy response measurements	Yuen KV. Beck JL.
771	Identification of parametric ground motion random fields from spatially recorded seismic data	Zerva A. Beck JL.
793	Experimental study on multiple tuned mass dampers to reduce seismic responses of a three-storey building structure	Chen G. Wu JN.
811	Steel frames with bracing mechanism and hysteretic dampers	Phocas MC. Pocanschi A.

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827	Effect of earthquake energy input characteristics on hysteretic damper efficiency	Yamaguchi H. El-Abd A.
845	Identification of soil degradation during earthquake excitations by bayesian inference	Ching JY. Glaser SD.
871	A unified formulation of the piecewise exact method for inelastic seismic demand analysis including the p-delta effect	Aydinoglu MN. Fahjan YM.
891	An experimental study of nominally symmetric and asymmetric structures isolated with the fps	de la Llera JC. Almazan JL.
919	Accidental torsion due to overturning in nominally symmetric structures isolated with the fps	Almazan JL. de la Llera JC.
949	Multiple active-passive tuned mass dampers for structures under the ground acceleration	Li CX.
965	A rooftop tuned mass damper frame	Johnson JG. Reaveley LD. Pantelides C.

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837	Foreword - fracture mechanics of concrete and concrete structures - 4th international framcos conference, held in cachan, france, from may 28 to june 1, 2001	van Mier JGM. Mazars J. Pijaudier-Cabot G. de Borst R.
839	Fracture mechanics of reactive powder concrete: material modelling and experimental investigations	Bayard O. Ple O.
853	A design approach for the mechanical properties of polypropylene discontinuous fiber reinforced cementitious composites by extrusion molding	Takashima H. Miyagai K. Hashida T. Li VC.
871	Elements of chemomechanics of calcium leaching of cement-based materials at different scales	Ulm FJ. Lemarchand E. Heukamp FH.
891	Environmentally induced deterioration of concrete: physical motivation and numerical modeling	Bangert F. Grasberger S. Kuhl D. Meschke G.
911	Microstructure and fracture in three dimensions	Landis EN. Nagy EN. Keane DT.
927	3d lattice type fracture model for concrete	Lilliu G. van Mier JGM.
943	Study of avalanches during the fracture of discrete models	Delaplace A. Roux S. Pijaudier-Cabot G.

957	Process zone resolution by extended finite elements	Patzak B. Jirasek M.
979	Size effect in concrete beams	Karihaloo BL. Abdalla HM. Xiao QZ.
995	Size effects on flexural response of reinforced concrete elements with a nonlinear matrix	Carpinteri A. Ferro G. Ventura G.
1015	Using numerical simulations to compare the fracture toughness values for concrete from the size-effect, two-parameter and fictitious crack models	Hanson JH. Ingraffea AR.
1029	Computational fracture analysis of concrete gravity dams by crack-embedded elements - toward an engineering evaluation of seismic safety	Horii H. Chen SC.
1047	Cracking in shotcrete tunnel shells	Lackner R. Mang HA.
1069	Non-linear model for r/c tensile members strengthened by frp-plates	Ferretti D. Savoia M.
1085	The equivalent reinforced concrete model for simulating the behavior of walls under dynamic shear loading	Kotronis P. Mazars J. Davenne L.

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1101	R-curve behavior in fracture of notched porous ceramics	Tanaka K. Akiniwa Y. Kimachi H. Kita Y.
1115	A modified kachanov method for analysis of solids with multiple cracks	Li YP. Tham LG. Wang YH. Tsui Y.
1131	Separability property and eta(pl) factor in astm a387-gr22 steel plate	Cassanelli AN. Cocco R. de Vedia LA.
1143	Fatigue of alumina under contact loading	Fett T. Keller R. Munz D. Ernst E. Thun G.
1153	A finite element analysis of stable crack growth in an aluminium alloy	Cheung S. Luxmoore AR.
1171	Approximate weight function method for elliptical arc through cracks in mechanical joints	Heo SP. Yang WH.
1193	An experimental technique to determine critical stress intensity factors for delamination initiation	Xie WD. Sitaraman SK.
1203	Piezoelectric sensor for stress intensity factor measurement of two dimensional cracks	Fujimoto Y. Shintaku E. Pirker G. Liu G.
1219	Paper: ”higher-order strain/higher-order stress gradient models derived from a discrete microstructure, with application to fracture”, by c.s chang, h. askes and l.j. sluys; engineering fracture mechanics 69 (2002), 1907-1924	Borino G. Polizzotto C.
1223	Paper: ”higher-order strain/higher-order stress gradient models derived from a discrete microstructure, with application to fracture”, by c.s chang, h. askes and l.j. sluys; engineering fracture mechanics 69 (2002), 1907-1924 - reply to letter to the editor as written by g. borino and c. polizzotto	Chang CS. Askes H. Sluys LJ.

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1227	Cracking in coating-substrate composites with multi-layered and fgm coatings	Chi SH. Chung YL.
1245	Experimental analysis of the practical lbz effects on the brittle fracture performance of cryogenic steel hazs with respect to crack arrest toughness near fusion line	Jang JI. Lee BW. Ju JB. Kwon D. Kim WS.
1259	Fatigue life and crack path predictions in generic 2d structural components	Miranda ACO. Meggiolaro MA. Castro JTP. Martha LF. Bittencourt TN.
1281	Cyclic plasticity at pores and inclusions in cast al-si alloys	Fan JH. McDowell DL. Horstemeyer MF. Gall K.
1303	Using strain gages to investigate subsonic dynamic interfacial fracture in an isotropic-isotropic bimaterial	Ricci V. Shukla A. Kavaturu M.
1323	A numerical fracture analysis of indentation into thin hard films on soft substrates	Sriram K. Narasimhan R. Biswas SK.
1339	Fracturing behaviors of frp-strengthened concrete structures	Wu ZS. Yin J.

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517	Foreword to: advanced stability and seismicity concepts	Watanabe E. Leon RT. Sugiura K. DesRoches R.
519	In memoriam: dr. egor p. popov	Malley J.
525	Behavior to complete failure of steel beams subjected to cyclic loading	Liu D. Nakashima M. Kanao I.
537	Cyclic shear force-slip behavior of studs under alternating and pulsating load condition	Nakajima A. Saiki I. Kokai M. Doi K. Takabayashi Y. Ooe H.
547	Classification of material and welding in fracture consideration of seismic steel frames	Kuwamura H.
565	Using co2 emission quantities in bridge lifecycle analysis	Itoh Y. Kitagawa T.
579	Application of an optimum design method to practical building frames with viscous dampers and hysteretic dampers	Uetani K. Tsuji M. Takewaki I.
593	Control of nonlinear bridge response with pounding effect by variable dampers	Ruangrassamee A. Kawashima K.
607	Seismic resistance of cft trusses	Kawano A. Sakino K.

621	Seismic retrofitting techniques using an energy absorption segment for steel bridge piers	Kitada T. Matsumura M. Otoguro Y.
637	Seismic drift and ductility demands and their dependence on ground motions	Krawinkler H. Medina R. Alavi B.
655	Seismic demands on steel braced frame buildings with buckling-restrained braces	Sabelli R. Mahin S. Chang C.
667	Ductile details for welded unreinforced moment connections subject to inelastic cyclic loading	Ricles JM. Mao CS. Lu LW. Fisher JW.
681	Towards deformation-based capacity design of rcs beam-column connections	Parra-Montesinos GJ. Liang X. Wight JK.
691	Stability and low-cycle fatigue limits of moment connection rotation capacity	Stojadinovic B.

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701	To retrofit or not to retrofit?	Nuti C. Vanzi I.
713	A review of time-frequency methods for structural vibration analysis [review]	Neild SA. McFadden PD. Williams MS.
729	Thermo-mechanic model for concrete exposed to elevated temperatures	Luccioni BM. Figueroa MI. Danesi RF.
743	Time-history analysis of urm walls in out-of-plane flexure	Lam NTK. Griffith M. Wilson J. Doherty K.
755	Column buckling of structural bamboo	Yu WK. Chung KF. Chan SL.
769	A shallow shell finite element for the linear and non-linear analysis of cylindrical shells	Djoudi MS. Bahai H.
779	Joint slip in steel electric transmission towers	Ungkurapinan N. Chandrakeerthy SRD. Rajapakse RKND. Yue SB.
789	Parametric resonance in cylindrical shells: a case study in the nonlinear vibration of structural shells	Popov AA.
801	Control of cable vibrations using secondary cable with special reference to nonlinearity and interaction	Yamaguchi H. Alauddin M.
817	A generalised steel/reinforced concrete beam-column element model for fire conditions	Cai J. Burgess I. Plank R.
835	Cyclic behaviour of a full scale rc structural wall	Riva P. Meda A. Giuriani E.
847	Variability in seismic response of secondary systems due to uncertain soil properties (vol 24, pg 1601, 2002)	Chaudhuri SR. Gupta VK.

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1	On the influence of stress triaxiality and strain rate on the behaviour of a structural steel. part i. experiments	Hopperstad OS. Borvik T. Langseth M. Labibes K. Albertini C.
15	On the influence of stress triaxiality and strain rate on the behaviour of a structural steel. part ii. numerical study	Borvik T. Hopperstad OS. Berstad T.
33	Calibration of nonlocal damage model from size effect tests	Le Bellego C. Dube LF. Pijaudier-Cabot G. Gerard B.
47	Effect of structural defects on the strength and damping properties of a solid material	Ouis D.
55	An energy based analysis of the pull-out problem	Bilteryst F. Marigo JJ.
71	A view on anisotropic finite hyper-elasticity	Menzel A. Steinmann P.
89	Morphology-based homogenization for viscoelastic particulate composites: part i: viscoelasticity sole	Nadot-Martin C. Trumel H. Dragon A.
107	An example of stick-slip and stick-slip-separation waves	Moirot F. Nguyen QS. Oueslati A.
119	Neutral stability of, and resonances in, a vertically stratified floating ice layer	Brevdo L.
139	Coupled instabilities in thin-walled beams: a qualitative approach	Pignataro M. Ruta GC.
151	The response of a finite beam on a tensionless pasternak foundation subjected to a harmonic load	Coskum I.
163	Flexural waves scattering by a through crack in a magnetically saturated mindlin plate under a uniform magnetic field	Ogihara A. Shindo Y. Horiguchi K.

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3	Nonlinear oscillations in three-armed tubes	Hirata K. Craik ADD.
27	Comparison of a lattice boltzmann simulation of steep internal waves and laboratory measurements using particle image velocimetry	Buick JM. Martin AJ. Cosgrove JA. Greated CA. Easson WJ.
39	Instability of a nearly inextensible thin layer in a shear flow	Charru F. Luchini P. Ern P.
51	Vapor flows with evaporation and condensation in the continuum limit: effect of a trace of noncondensable gas	Aoki K. Takata S. Taguchi S.
73	An iterative procedure for solving mixed convection boundary layers with reverse flows	Amaouche M. Meziani B.
85	Flow separation between rotating eccentric cylinders	de Socio LM. Marino L.

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1	Overview of optical techniques that measure displacements: murray lecture	Sciammarella CA.
20	Dynamic small strain measurements of a metal specimen with a split hopkinson pressure bar	Chen W. Song B. Frew DJ. Forrestal MJ.
24	Inspection of interfaces between corroded steel bars and concrete using the combination of a piezoelectric zirconate-titanate transducer and an electromagnetic acoustic transducer	Na WB. Kundu T.
32	Measurement techniques in the testing of thin-walled structural members	Young B. Rasmussen KJR.
39	Development of a portable shear test fixture for low modulus porous (foam) materials	Roy AK. Camping JD.
45	Strain analysis for moire interferometry using the two-dimensional continuous wavelet transform	Kadooka K. Kunoo K. Uda N. Ono K. Nagayasu T.
52	Three-dimensional stress-relief displacements from blind-hole drilling: a parametric description	Rumzan I. Schmitt DR.
61	Full-field strain measurement using a luminescent coating	Hubner JR. Ifju PG. Schanze KS. Jenkins DA. Carroll BF. Wang YS. He P. Brennan A. El-Ratal W.
69	Measurement of residual internal stresses in optical fiber preforms	Pagnotta L. Poggialini A.
77	Reduction of k-i and k-ii by the shape-memory effect in a tini shape-memory fiber-reinforced epoxy matrix composite	Shimamoto A. Azakami T. Oguchi T.
83	Real-time analysis of isochromatics and isoclinics using the phase-shifting method	Yoneyama S. Morimoto Y. Nomura T. Fujigaki M. Matsui R.
90	Performance evaluation of accelerometers used for penetration experiments	Forrestal MJ. Togami TC. Baker WE. Frew DJ.
97	Determination of residual stresses by an optical correlative hole-drilling method	Focht G. Schiffner K.
105	X-ray residual stress measurement on mechanical components with high curvature	Berruti T. Gola MM.

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156	Tomographic particle-image velocimetry and thermography in rayleigh-benard convection using suspended thermochromic liquid crystals and digital image processing	Ciofalo M. Signorino M. Simiano M.
173	Analogy between soap film and gas dynamics. ii. experiments on one-dimensional motion of shock waves in soap films	Wen CY. Chang-Jian SK. Chuang MC.
181	Turbulence under spilling breakers using discrete wavelets	Longo S.
192	A new laser vorticity probe - lavor: its development and validation in a turbulent boundary layer	Agui JH. Andreopoulos Y.
206	Interfacial structure of air-water two-phase flow in a relatively large pipe	Sun X. Smith TR. Kim S. Ishii M. Uhle J.
220	Plane mixing layers from parallel and non-parallel merging of two streams	Azim MA. Islam AKMS.
227	Three-dimensional voronoi imaging methods for the measurement of near-wall particulate flows	Spinewine B. Capart H. Larcher M. Zech Y.
242	Velocity statistics and flow structures observed in bypass transition using stereo ptv	Inasawa A. Lundell F. Matsubara M. Kohama Y. Alfredsson PH.
253	Measurements and scaling of wall shear stress fluctuations	Colella KJ. Keith WL.
261	Effect of different sized transverse square grooves on a turbulent boundary layer	Sutardi. Ching CY.
275	Visualization of air flow using infrared thermography	Narayanan V. Page RH. Seyed-Yagoobi J.
285	An approximate amplitude attenuation correction for hot-film shear stress sensors	Kinkel GJ. Marusic I.
291	Quantitative studies of the wakes of freely flying birds in a low-turbulence wind tunnel	Spedding GR. Hedenstrom A. Rosen M.
304	Measurement of rotating flows using piv and image derotation	Stickland MT. Scanlon TJ. Waddell P. Fernandez-Francos J. Blanco E.

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307	Flow measurement on oscillating pipe flow near the entrance using the uvp method	Yamanaka G. Kikura H. Takeda Y. Aritomi M.
316	A study on the relation between flow characteristics and cluster formation of electrorheological fluid using visualization	Rhee EJ. Park MK. Yamane R. Oshima S.
324	Details on the intermittent transition to turbulence of a locally forced plane couette flow	Antar G. Bottin S. Dauchot O. Daviaud F. Manneville P.
332	Free-stream turbulence effects on the instantaneous pressure and forces on cylinders of rectangular cross section	Noda H. Nakayama A.
345	On multiple-path sonic anemometer measurement theory	Cuerva A. Sanz-Andres A. Navarro J.
358	Uncertainty analysis of four-sensor hot-wires and their data-reduction schemes used in the near field of a turbulent jet	Lavoie P. Pollard A.

371	Laser-optical investigation of turbine wake flow	Woisetschlager J. Mayrhofer N. Hampel B. Lang H. Sanz W.
379	Study of the flow around surface-mounted pyramids	Martinuzzi RJ. AbuOmar M.
390	Tracking of coherent thermal structures on a heated wall. 2. dns simulation	Kowalewski TA. Mosyak A. Hetsroni G.
397	Time-dependent drag reduction and ageing in aqueous solutions of a cationic surfactant	Nowak M.
403	Comparison of molecular tagging velocimetry data and direct simulation monte carlo simulations in supersonic micro jet flows	Lempert WR. Boehm M. Jiang N. Gimelshein S. Levin D.
412	Experimental study of the stability of long axisymmetric liquid bridges between solid supports at different temperatures	Luengo V. Meseguer J. Parra IE.
418	Experimental study of the velocity field in a vortex-flow heat exchanger with isothermal conditions	Petitot S. Lyazid A. Devienne R.
430	Planar velocity measurements of a two-dimensional compressible wake	Scarano F. van Oudheusden BW.
442	Laser doppler velocimetry measurements in an interior flow test facility: a database for cfd-code evaluation	Mocikat H. Gurtler T. Herwig H.

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293	Fracture and manufacturing: selected papers from euromech colloquium 418	Goldstein R. Atkins T.
295	The effects of macrolocalization of deformation in al-based composites with al2o3 inclusions	Deryugin YY. Panin VE. Schmauder S. Soppa E.
305	An approach to determining the workability diagram based on upsetting tests	Vilotic D. Planck M. Grbic S. Alexandrov S. Chikanova N.
311	Modelling macroscopic imperfections for the prediction of flow localization and fracture	Barlat F. Richmond O.
323	Detection of crack nucleation in sheet metalforming by monitoring infrared radiation	Andrianopoulos NP. Champidis KT. Iliopoulos AP.
329	The effects of loading waveform and microstructure on the fatigue response of titanium aero-engine compressor disk alloys	Shaniavski AA. Losev AI.
343	Stress and fracture analysis in periodic contact problem for coated bodies	Goryacheva IG. Torskaya EV.
349	Structure and mesoscale plastic deformation and fracture patterns of materials coated by electron-beam deposition	Panin VE. Belyuk SI. Durakov VG. Panin SV. Galchenko NK. Samartsev VP.
363	Structural macromechanics approach in dynamics of fracture	Petrov YV. Morozov NF. Smirnov VI.
373	Definition of the kinetic equation form for damage under the plastic deformation	Smirnov SV. Domilovskaya TV.

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383	A statistical approach to strength evaluation incorporating porosity effect for porous ceramics	Hoshide T. Abe J.
391	Strength estimation of ceramic-metal joints with various interlayer thickness	Takahashi M. Okabe N. Zhu X. Kagawa K.
399	Influence of anisotropy on a limit load of weld strength overmatched middle cracked tension specimens	Alexandrov S. Gracio J.
405	Reliability analysis of hybrid ceramic/steel gun barrels	Grujicic M. DeLong JR. Derosset WS.
421	Fatigue crack propagation of through cracks in thin sheets under combined traction and bending stresses	Lanciotti A. Polese C.
429	Crack growth induced delamination on steel members reinforced by prestressed composite patch	Colombi P. Bassetti A. Nussbaumer A.
439	Fatigue behaviour of a box-welded joint under biaxial cyclic loading: effects of biaxial load range ratio and cyclic compressive loads in the lateral direction	Takahashi I. Takada A. Ushijima M. Akiyama S.
449	Crushing behaviour of the energy absorbing 'tensor skin' panels	Labeas G. Kermanidis TH.
459	A procedure for estimating the total life in fretting fatigue	Navarro C. Garcia M. Dominguez J.
469	On the estimation of fatigue failure under fretting conditions using notch methodologies	Vallellano C. Dominguez J. Navarro A.
479	Application of interface finite elements to three-dimensional progressive failure analysis of adhesive joints	Goncalves JPM. de Moura MFSF. Magalhaes AG. de Castro PMST.

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561	Three-dimensional transient elastodynamic analysis by a space and time-discontinuous galerkin finite element method	Chien CC. Yang CS. Tang JH.
581	Parallel computations of finite element output bounds for conjugate heat transfer	Cheng Z. Paraschivoiu M.
599	Fe analysis of large deformations of membranes with wrinkling	Stanuszek M.

619	Efficient finite element analysis using mesh superposition technique	Park JW. Hwang JW. Kim YH.
639	An automated incremental finite element study of hertzian cone crack growth	Kocer C.
661	Integrated design method for flip chip csp with electrical, thermal and thermomechanical qualifications	Liu DS. Ni CY. Chen CY.

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119	Bifurcations and inviscid limit of rhombic navier-stokes flows in tori	Kim SC. Okamoto H.
135	Solvability of a non-local hyperbolic model arising from a reliability system	Ackleh AS. Deng K. Li W.
149	The efficient computation of periodic states of cyclically operated chemical processes	van Noorden TL. Lunel SMV. Bliek A.
167	Absorbing boundary conditions for reaction-diffusion equations	Szeftel J.
185	Buckling of a timoshenko beam on elastic foundation with uncertain input data	Hlavacek I.
205	Bifurcation analysis of surge and rotating stall in the moore-greitzer compression system	Hos C. Champneys A. Kullmann L.

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159	Fast iterative solution of large undrained soil-structure interaction problems	Phoon KK. Chan SH. Toh KC. Lee FH.
183	Solid-liquid-air coupling in multiphase porous media	Laloui L. Klubertanz G. Vulliet L.
207	The response of an elastic half-space under a momentary shear line impulse	Ziv M.

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259	Modelling of a snowpack in interaction with a flexible structure using a coupled lagrangian-discrete approach	Nicot F. Gagliardini O. Boutillier B.
275	Extension of the griffith's fracture criteria to saturated clays	Degue KM. Soulie M. Ladanyi B.
289	Kinematic modelling of shear band localization using discrete finite elements	Wang X. Chan D. Morgenstern N.
325	Numerical investigations of shear localization in a micro-polar hypoplastic material	Huang WX. Bauer E.

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353	Direct assessment of structural resistance against pressurized fracture	Bolzon G. Cocchetti G.
379	Inter-relations between experimental and computational aspects of slope stability analysis	Baker R.
403	A micromechanical study of rolling and sliding contacts in assemblies of oval granules	Shodja HM. Nezami EG.
425	Capturing strain localization behind a geosynthetic-reinforced soil wall	Lai TY. Borja RI. Duvernay BG. Meehan RL.

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935	A reproducing kernel method with nodal interpolation property	Chen JS. Han WM. You Y. Meng XP.
961	Non-uniform plastic deformation of micron scale objects	Niordson CF. Hutchinson JW.
977	Voxel-based meshing and unit-cell analysis of textile composites	Kim HJ. Swan CC.
1007	Mesh deformation using the biharmonic operator	Helenbrook BT.
1023	Transient analysis of electro-osmotic transport by a reduced-order modelling approach	Qiao R. Aluru NR.
1051	On the strong discontinuity approach in finite deformation settings	Oliver J. Huespe AE. Pulido MDG. Samaniego E.

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1083	Efficient implicit finite element analysis of sheet forming processes	van den Boogard AH. Meinders T. Huetink J.
1109	Natural hierarchical refinement for finite element methods	Krysl P. Grinspun E. Schroder P.

1125	Optimization of thermo-elasto-plastic processes using eulerian sensitivity analysis	Paul S. Michaleris P. Shanghvi JY.
1151	Stress intensity factor analysis of interface cracks using x-fem	Nagashima T. Omoto Y. Tani S.
1175	Application of symmetric indirect trefftz method to free vibration problems in 2d	Chang JR. Liu RF. Kuo SR. Yeih WC.
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2015	Brittle fracture in polycrystalline microstructures with the extended finite element method	Sukumar N. Srolovitz DJ. Baker TJ. Prevost JH.
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2101	An analysis of strain localization in a shear layer under thermally coupled dynamic conditions. part 2: localized thermoplastic models	Armero F. Park J.
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2199	Failure analysis of solder joints with a damage-coupled viscoplastic model	Wei Y. Chow CL. Neilsen MK. Fang HE.
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2313	An adaptive non-conforming finite-element method for reissner-mindlin plates	Carstensen C. Weinberg K.
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35	Unequally spaced non-periodic b-spline finite strip method	Choi CK. Hong HS. Kim KH.
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83	A new fixed-point algorithm for hardening plasticity based on non-linear mixed variational inequalities	Venini P. Nascimbene R.
103	Non-local boundary integral formulation for softening damage	Sladek J. Sladek V. Bazant ZP.
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951	A godunov method for the computation of erosional shallow water transients	Fraccarollo L. Capart H. Zech Y.
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871	Determining material constants in micromorphic theory through phonon dispersion relations	Chen YP. Lee JD.
887	Combined isotropic and kinematic hardening in phenomenological switching models for ferroelectric ceramics	Haug A. Knoblauch V. McMeeking RM.
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1109	A complete stress update algorithm for the non-associated drucker-prager model including treatment of the apex	Hjiai M. Fortin J. de Saxce G.
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201	A neural network approach to describing the fretting fatigue in aluminium-steel couplings	Orbanic P. Fajdiga M.
209	Low cycle fatigue crack growth and life prediction of short-fibre reinforced aluminium matrix composites	Ding HZ. Biermann H. Hartmann O.
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231	Statistical analysis for application of the paris equation to whisker reinforced metal matrix composites	Ahn JJ. Ochiai S.
237	Statistical design and orthogonal polynomial model to estimate the tensile fatigue strength of wooden finger joints	Martinez ME. Calil CJ.
245	Influence of porosity on the fatigue limit of die cast magnesium and aluminium alloys	Mayer H. Papakyriacou M. Zettl B. Stanzl-Tschegg SE.
257	The use of closure maps to characterise plasticity induced crack closure	McKellar DK. Nowell D. Hills DA.

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299	The development of an optimisation algorithm based on fatigue life	Haiba M. Barton DC. Brooks PC. Levesley MC.
311	Effect of fatigue damage on the dynamic response frequency of spot-welded joints	Shang DG. Barkey ME. Wang Y. Lim TC.
317	Theoretical modeling of crack arrest by inserting interference fit fasteners	Shkarayev S.
325	Mixed mode fatigue crack growth in aluminum plates with composite patches	Chung KH. Yang WH.
335	A statistical approach for predicting the crack retardation due to a single tensile overload	Kim JK. Shim DS.
343	Correlation between thermography and internal damping in metals	Audenino AL. Crupi V. Zanetti EM.
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397	Near threshold fatigue crack growth in aluminium alloys at low and ultrasonic frequency: influences of specimen thickness, strain rate, slip behaviour and air humidity	Holper B. Mayer H. Vasudevan AK. Stanzl-Tschegg SE.
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427	A practical method for statistical analysis of strain-life fatigue data	Williams CR. Lee YL. Rilly JT.
437	Observations on damage development in fibre reinforced polymer laminates under cyclic loading	Wharmby AW. Ellyin F. Wolodko JD.
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9	Screw dislocation interacting with an interfacial edge crack between two bonded dissimilar piezoelectric wedges	Wu XF. Dzenis YA. Zou WS.
15	On a crack in viscoelastic isotropic media opened by a rigid growing wedge	Kaminsky AA. Chernoivan YA.
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29	The effect of a plastically deformed zone near cracktip on the stress intensity factors	Li ZH. Duan JY.
35	Effect of a minimal spacing between inhomogeneities on the effective moduli of isotropic plates with circular inhomogeneities	Shen LX. Li J.
297	Effects of plastic anisotropy on crack-tip behaviour	Legarth BN. Tvergaard V. Kuroda M.
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323	Numerical solution of cracked thin plates subjected to bending, twisting and shear loads	Su RKL. Sun HY.
337	Path-independent integral for the dilatation symmetry group in thermoplasticity	Sansen P. Dufrenoy P. Weichert D.
347	Numerical modeling of size effects with gradient elasticity - formulation, meshless discretization and examples	Askes H. Aifantis EC.
359	Mechanism of effects of warm prestressing(wps) on apparent toughness of notched steel specimens: part 1: experimental	Wang GZ. Dong ZQ. Chen JH. Chen X.
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3	A method of evaluation of transverse critical energy release rate (fiber failure mode) in advanced composites	Dzenis YA. Qin MH. Pagano NJ.
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15	Effects of electric boundary conditions on electroelastic field in a cracked piezoelectric strip	Li XF. Tang BQ.
17	The optimal control of fracture and stress parameters in a piezoceramic halfspace with cracks	Bardzokas DI. Filshtinsky ML. Rodriguez-Ramos R. Sanchez-Casals O.
29	Crack-inclusion interaction for mode i crack analyzed by eshelby equivalent inclusion method	Li ZH. Chen Q.
41	The numerical solutions of the periodic crack problems of anisotropic strips	Li X. Wu YJ.
57	On the characteristic distance and minimum fracture toughness for cleavage fracture in a c-mn steel	Wang GZ. Chen JH. Liu GH.
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37	Elastoplastic behavior of two-dimensional solids with rectilinear cracks under mixed-mode loading	Grychanyuk V. Tsukrov I.
99	A probabilistic model for cleavage fracture with a length scale-influence of material parameters and constraint	Kroon M. Faleskog J.
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51	Derivative procedure for bem based computation of change in natural frequency with crack size	Medhekar NV. Maiti SK.
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229	Material forces due to crack-inclusion interaction	Kolling S. Baaser H. Gross D.
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157	Investigation of wall-function approximations and subgrid-scale models in large eddy simulation of separated flow in a channel with streamwise periodic constrictions	Temmerman L. Leschziner MA. Mellen CP. Frohlich J.
181	An investigation of wall-anisotropy expressions and length-scale equations for non-linear eddy-viscosity models	Abe K. Jang YJ. Leschziner MA.
199	Effects of acoustic excitation positions on heat transfer and flow in axisymmetric impinging jet: main jet excitation and shear layer excitation	Hwang SD. Cho HH.
210	Heat transfer mechanisms in vapor mushroom region of saturated nucleate pool boiling	Wei JJ. Yu B. Wang HS.
223	Coupled liquid film and solidified layer growth with impinging supercooled droplets and joule heating	Naterer GF.
236	Friction factor at low knudsen number for the duct with sine-shaped cross-section	Pinazza O. Spiga M.
242	The droplet number moments approach to spray modelling: the development of heat and mass transfer sub-models	Beck JC. Watkins AP.

260	Pressure drop correlation for laminar, mixed convection, aiding flow heat transfer in a vertical tube	Joye DD.
267	Optimization of heat transfer utilizing graph based evolutionary algorithms	Bryden KM. Ashlock DA. McCorkle DS. Urban GL.
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1139	Analysis of forced convection heat transfer to supercritical carbon dioxide inside tubes using neural networks	Scalabrin G. Piazza L.
1155	Inverse influence of initial diameter on droplet burning rate in cold and hot ambiences: a thermal action of flame in balance with heat loss	Xu GW. Ikegami M. Honma S. Ikeda K. Ma XX. Nagaishi H. Dietrich DL. Struk PM.
1171	Study on point of net vapor generation by neutron radiography in subcooled boiling flow along narrow rectangular channels with short heated length	Kureta M. Hibiki T. Mishima K. Akimoto H.
1183	A direct three-dimensional simulation of radiation-induced natural convection in a shallow wedge	Lei CW. Patterson JC.
1199	Experimental and numerical analysis of the temperature transition of a suspended freezing water droplet	Hindmarsh JP. Russell AB. Chen XD.
1215	Geometric and aero-thermal influences on multiholed plate temperature: application on combustor wall	Leger B. Miron P. Emidio JM.
1223	Nucleate pool boiling characteristics from coated tube bundles in saturated r-134a	Hsieh SS. Huang GZ. Tsai HH.
1241	Cooling enhancement in an air-cooled finned heat exchanger by thin water film evaporation	Song CH. Lee DY. Ro ST.
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1265	Aerodynamic and mass transfer characteristics of an annular bistable impinging jet with a fluidic flip-flop control	Travnicek Z. Peszynski K. Hosek J. Wawrzyniak S.
1279	Investigation of the evaporation of embedded liquid droplets from porous surfaces using magnetic resonance imaging	Reis NC. Griffiths RF. Mantle MD. Gladden LF.
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1321	Minimization of entropy generation by asymmetric convective cooling	Ibanez G. Cuevas S. de Haro ML.
1329	Heat conduction across irregular and fractal-like surfaces	Blyth MG. Pozrikidis C.
1341	Structure of mixed convective longitudinal vortex air flow driven by a heated circular plate embedded in the bottom of a horizontal flat duct	Tuh JL. Lin TF.
1359	Fully developed electro-osmotic heat transfer in microchannels	Maynes D. Webb BW.
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1395	Interactions between molten metal droplets impinging on a solid surface	Ghafouri-Azar R. Shakeri S. Chandra S. Mostaghimi J.
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1425	Periodicity and bifurcations in capillary tube boiling with a concentric heating wire	Acharya N. Sen M. Ramos E.
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1529	Large eddy simulation of turbulent channel flow with mass transfer at high-schmidt numbers	Dong YH. Lu XY. Zhuang LX.
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1553	Three-dimensional numerical optimization of a manifold microchannel heat sink	Ryu JH. Choi DH. Kim SJ.
1563	Conjugate heat transfer in inclined open shallow cavities	Polat O. Bilgen E.
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1599	Magnetic field effects upon heat transfer for laminar flow of electrically conducting liquid over a melting slab	Seeniraj RV. Kannan NP.
1607	Thermal waves propagation in porous material undergoing thermal loading	Sluzalec A.
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1653	3d modeling of evaporation of water injected into a plasma jet	Ramachandran K. Sato T. Nishiyama H.
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1715	Mass transfer into liquid falling film in straight and helically coiled tubes	Hameed MS. Muhammed MS.
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2027	Fin-tube junction effects on flow and heat transfer in flat tube multilouvered heat exchangers	Tafti DK. Cui J.
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2065	Determination of a heat source in porous medium with convective mass diffusion by an inverse method	Prud'homme M. Jasmin S.
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2095	Study on transport phenomena for flow film condensation in vertical mini-tube with interfacial waves	Du XZ. Wang BX.

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2115	Three-dimensional double-diffusive convection and macrosegregation during non-equilibrium solidification of binary mixtures	Chakraborty S. Dutta P.
2135	An analytical solution for two-dimensional inverse heat conduction problems using laplace transform	Monde M. Arima H. Liu W. Mitutake Y. Hammad JA.
2149	Role of the contact layer between liquid and solid on a solidification process	Lipnicki Z.
2155	Numerical technique for modeling conjugate heat transfer in an electronic device heat sink	Horvat A. Catton I.
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2179	Two-dimensional model of heat transfer in circulating fluidized beds. part i: model development and validation	Xie D. Bowen BD. Grace JR. Lim CJ.
2193	Two-dimensional model of heat transfer in circulating fluidized beds. part ii: heat transfer in a high density cfb and sensitivity analysis	Xie D. Bowen BD. Grace JR. Lim CJ.
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2219	Surfactant effects on passive scalar transport in a fully developed turbulent flow	Handler RA. Leighton RI. Smith GB. Nagaosa R.
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499	Taylor impact test for ductile porous materials - part 2: experiments	Wang B. Zhang J. Lu G.
513	Shear plugging and perforation of ductile circular plates struck by a blunt projectile	Chen XW. Li QM.
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627	Fracture behavior of cfrps impacted by relatively high-velocity steel sphere	Tanabe Y. Aoki M. Fujii K. Kasano H. Yasuda E.
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743	Perforation of a thick plate by rigid projectiles	Chen XW. Li QM.
761	Experimental and theoretical study of free-free beam subjected to impact at any cross-section along its span	Yang JL. Xi F.
783	A finite element to simulate the failure of weld points on impact	Combescure A. Delcroix F. Caplain L. Espanol S. Eliot P.
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849	Low and high velocity impact on inconel 718 casting plates: ballistic limit and numerical correlation	Di Sciuva M. Frola C. Salvano S.
877	Investigation of dynamic flow and strength properties of ti-6-22-22s at normal and elevated temperatures	Kruger L. Meyer LW. Razorenov SV. Kanel GI.
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985	Effect of characteristics of materials on fracture behavior and modeling using graphite-related materials with a high-velocity steel sphere	Fujii K. Yasuda E. Akatsu T. Tanabe Y.
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2427	Numerical improvement of thin tubes hydroforming with respect to ductile damage	Cherouat A. Saanouni K. Hammi Y.
2447	Unsteady state work-roll temperature distribution during continuous hot slab rolling	Serajzadeh S. Taheri AK. Mucciardi F.

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2479	Buckling analysis of circular plates of functionally graded materials under uniform radial compression	Najafizadeh MM. Eslami MR.
2495	Ferrofluid lubrication in porous inclined slider bearing with velocity slip	Shah RC. Bhat MV.
2503	Vibration analysis of rectangular mindlin plates with internal line supports using static timoshenko beam functions	Zhou D. Lo SH. Au FTK. Cheung YK.
2523	Near net shape processing of a sintered alumina component: adjustment of pressing parameters through finite element simulation	Kim HG. Gillia O. Doremus P. Bouvard D.
2541	Vibration of an euler-bernoulli beam on elastic end supports and with up to three step changes in cross-section	Naguleswaran S.
2557	Lateral-torsional buckling of beams and the southwell plot	Mandal P. Calladine CR.
2573	2d rolling contact problem involving frictional heating	Pauk V. Zastrau B.
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1297	Non-isothermal oscillations of pseudoelastic devices	Bernardini D. Vestroni F.
1315	Dynamics of the geometrically non-linear analysis of anisotropic laminated cylindrical shells	Toorani MH.
1337	Bifurcation of water column oscillator behavior analyzed by two-dimensional graphical method	Yuichiro M. Haruki M.
1351	Effect of material non-homogeneity on the inhomogeneous shearing deformation of a gent slab subjected to a temperature gradient	Bilgili E. Bernstein B. Arastoopour H.
1369	Infinite interval problems arising in non-linear mechanics and non-newtonian fluid flows	Agarwal RP. O'Regan D.
1377	Exact solutions for some non-conservative hyperbolic systems	Joseph KT. Sachdev PL.
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1403	An eulerian approach of non-linear membrane shell theory	Millet O. Hamdouni A. Cimetiere A.
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1481	Large free vibrations of a beam carrying a moving mass	Siddiqui SAQ. Golnaraghi MF. Heppler GR.
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1581	Two-dimensional bilinear oscillator: group-preserving scheme and steady-state motion under harmonic loading	Liu CS.
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941	Fractional relaxation processes and fractional rheological models for the description of a class of viscoelastic materials	Metzler R. Nonnenmacher TF.
961	A macroscopic finite strain model for cellular polymers	Ehlers W. Markert B.
977	Visco-hyperelastic model with internal state variable coupled with discontinuous damage concept under total lagrangian formulation	Laiarinandrasana L. Piques R. Robisson A.
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1019	A phenomenological constitutive model for rubberlike materials and its numerical applications	Besdo D. Ihlemann J.
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1195	Experimental studies on the yield behavior of ductile and brittle aluminum foams	Doyoyo M. Wierzbicki T.
1215	Plastic flow for non-monotonic loading conditions of an aluminum alloy sheet sample	Barlat F. Duarte JMF. Gracio JJ. Lopes AB. Rauch EF.
1245	Finite element analysis of grain-by-grain deformation by crystal plasticity with couple stress	Kim HK. Oh SI.

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87	Stress concentration factors of nozzle-sphere connections	Schindler S. Zeman JL.
97	Constitutive equations for time independent plasticity and creep of 316 stainless steel at 550 degrees c	Hayhurst DR. Vakili-Tahami F. Zhou JQ.
111	A simulation of fatigue crack propagation in a welded t-joint using 3d boundary element method	Xiang ZH. Lie ST. Wang B. Cen ZZ.
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129	Evaluation of interfacial crack growth in bimaterial metallic joints loaded by symmetric three-point bending	Jiang F. Zhao K. Sun J.
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1059	A nonlinear theory for doubly curved anisotropic sandwich shells with transversely compressible core	Hohe J. Librescu L.
1089	Application of theorem of minimum potential energy to a complex structure part i: two-dimensional analysis	Preissner EC. Vinson JR.
1109	Application of theorem of minimum potential energy to a complex structure part ii: three-dimensional analysis	Preissner EC. Vinson JR.
1139	A failure criterion for fiber reinforced polymer composites under combined compression-torsion loading	Yerramalli CS. Waas AM.
1165	A semi-analytical elastic stress-displacement solution for notched circular openings in rocks	Exadaktylos GE. Liolios PA. Stavropoulou MC.
1189	Finite element calculation of elastodynamic stress field around a notch tip via contour integrals	Chang JH. Wu DJ.
1203	Effects of pretwist and presetting on coupled bending vibrations of rotating thin-walled composite beams	Oh SY. Song O. Librescu L.
1225	Microstructure-based stress analysis and evaluation for porous ceramics by homogenization method with digital image-based modeling	Takano N. Zako M. Kubo F. Kimura K.

1243	Characterization of anisotropy in porous media by means of linear intercept measurements	Inglis D. Pietruszczak S.
1265	Wind-rain-induced vibration of cable: an analytical model (1)	Wang LY. Xu YL.
1281	Non-linear micropolar and classical continua for anisotropic discontinuous materials	Trovalusci P. Masiani R.
1299	Interfacial friction in the debonded structural cell of particulate rubber composites	Koltsov AS. Sursjakov VA. Moshev VV.
1311	A semi-analytical buckling analysis of imperfect cylindrical shells under axial compression	Jamal M. Lahlou L. Midani M. Zahrouni H. Limam A. Damil N. Potier-Ferry M.
1329	Discussion on ”the asymmetry of stress in granular media” by j.p. bardet and i. vardoulakis - [int. j. solids and structures, vol. 38, pp. 353-367 (2001)]	Bagi K.
1333	Comments on ”effects of pre-stress on crack-tip fields in elastic, incompressible solids” by e. radi, d. bigoni, d. calmani	Guz AN.
1335	A galerkin boundary integral method for multiple circular elastic inclusions with homogeneously imperfect interfaces (vol 39, pg 4723, 2002)	Mogilevskaya SG. Crouch SL.

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1369	Energy relaxation of non-convex incremental stress potentials in a strain-softening elastic-plastic bar	Lambrecht M. Miehe C. Dettmar J.
1393	Effective elastic moduli of composites reinforced by particle or fiber with an inhomogeneous interphase	Shen LX. Li J.
1411	On the unified approach to anisotropic and isotropic elasticity for singularity, interface and crack in dissimilar media	Choi ST. Shin H. Earmme YY.
1433	A mixed electric boundary value problem for a two-dimensional piezoelectric crack	Huang ZY. Kuang ZB.
1455	Hencky’s logarithmic strain and dual stress-strain and strain-stress relations in isotropic finite hyperelasticity	Xiao H. Chen LS.
1465	A theory of amorphous solids undergoing large deformations, with application to polymeric glasses	Anand L. Gurtin ME.
1489	Damage evolution in particulate composite materials	Matous K.
1505	On the stress-wave imaging of cavities in a semi-infinite solid	Guzina BB. Fata SN. Bonnet M.
1525	Mechanical behaviour of laminated composite beam by the new multi-layered laminated composite structures model with transverse shear stress continuity	Karama M. Afaq KS. Mistou S.
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1567	Micromechanical concept for the analysis of damage evolution in thermo-viscoelastic and quasi-brittle materials	Stumpf H. Hackl K.
1585	Application of lie transformation group methods to classical linear theories of rods and plates	Vassilev VM. Djondjorov PA.

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1633	Effect of debonding in active constrained layer damping patches on hybrid control of smart beams	Sun DC. Tong LY.
1653	Failure in the junction region of t-stiffeners: 3d-braided vs. 2d tape laminate stiffeners	Yang QD. Rugg KL. Cox BN. Shaw MC.
1669	State vector approach to analysis of multilayered magneto-electro-elastic plates	Wang JG. Chen LF. Fang SS.
1681	Homogenization of two-phase elasto-plastic composite materials and structures - study of tangent operators, cyclic plasticity and numerical algorithms	Doghri I. Ouaar A.
1713	Extrema of young’s modulus for cubic and transversely isotropic solids	Cazzani A. Rovati M.
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1825	Structure and properties of the solution space of general anisotropic laminates	Yin WL.
1853	Analysis of shear band instabilities in compaction of powders	Redanz P. Tvergaard V.

1865	Analysis of tapered enf specimen and characterization of bonded interface fracture under mode-ii loading	Qiao PH. Wang JL. Davalos JF.
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2057	Interfacial viscoelastic sh waves	Romeo M.
2069	Strength reliability of statically indeterminate heterogeneous beams	Altus E. Givli S.
2085	Optimization of a metal honeycomb sandwich beam-bar subjected to torsion and bending	Wang AJ. McDowell DL.
2101	On green's function for a bimaterial elastic half-plane	Martin PA.
2121	Smoothing elastoplastic stress-strain curves obtained by a critical modification of conventional models	Liu CS.
2147	Dynamic response and energy dissipation characteristics of balsa wood: experiment and analysis	Vural M. Ravichandran G.
2171	A time dependent micro-mechanical fiber composite model for inelastic zone growth in viscoelastic matrices	Beyerlein IJ. Zhou CH. Schadler LS.
2195	Identification of orthotropic damages within a thin uniform plate	Lee U. Cho K. Shin J.
2215	Micro-stress prediction in composite laminates with high stress gradients	Hutapea P. Yuan FG. Pagano NJ.
2249	Biaxial flexural strength distribution of thin ceramic substrates with surface defects	Cheng M. Chen WO. Sridhar KR.
2267	A physically based continuum damage mechanics model for thin laminated composite structures	Williams KV. Vaziri R. Poursartip A.
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2321	The viscoelastic and viscoplastic behavior of low-density polyethylene	Drozdov AD. Yuan Q.
2343	Evolving crack patterns in thin films with the extended finite element method	Liang J. Huang R. Prevost JH. Suo Z.
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2401	Special virtual fields for the direct determination of material parameters with the virtual fields method. 3. application to the bending rigidities of anisotropic plates	Grediac M. Toussaint E. Pierron F.
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2487	A structural mechanics approach for the analysis of carbon nanotubes	Li CY. Chou TW.
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523	Performance analysis of bridge type gmr microaccelerometer by inverse method	Chen JJ. Weng CI. Chang JG.
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55	Identification of spring-force factors of suspension systems using progressive neural network on a validated computer model	Xu D. Yap FF. Han X. Wen GL.
75	Effects of the heating process and body dimensions on the estimation of the thermal conductivity components of orthotropic solids	Mejias MM. Orlande HRB. Ozisik MN.

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157	A real coded genetic algorithm approach for detection of subsurface isotropic and anisotropic inclusions	Mera NS. Elliott L. Ingham DB.

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10	An extended finite element method for two-phase fluids	Chessa J. Belytschko T.
18	An unstructured finite element solver for ship hydrodynamic's problems	Garcia J. Onate E.
27	Numerical solutions of cauchy-riemann, equations for two and three-dimensional flows	Hafez M. Housman J.
32	An overset finite-element large-eddy simulation method with applications to turbomachinery and aeroacoustics	Kato C. Kaiho M. Manabe A.
44	Hierarchical divergence-free bases and their application to particulate flows	Sarin V. Sameh AH.
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58	Mesh moving techniques for fluid-structure interactions with large displacements	Stein K. Tezduyar T. Benney R.
64	A method for particle simulation	Zhang Z. Prosperetti A.
75	Shear buckling of sandwich, fiber composite and lattice columns, bearings, and helical springs: paradox resolved	Bazant ZP.
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91	Generalized framework for three-dimensional upper bound limit analysis in a tresca material	Puzrin AM. Randolph MF.
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111	General solution for mechanical and thermal stresses in a functionally graded hollow cylinder due to nonaxisymmetric steady-state loads	Jabbari M. Sohrabpour S. Eslami MR.
119	Localization of vibration propagation in two-dimensional systems with multiple substructural modes	Xie WC.
129	Feedback stabilization of quasi-integrable hamiltonian systems	Zhu WQ. Huang ZL.
137	Squeeze film force using an elliptical velocity profile	Usha R. Vilmala P.
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147	Finite element analysis of brittle cracking due to single grit rotating scratch	Subhash G. Zhang W.
151	An alternative method of solving multilayer bending problems	Hsueh CH. Lee S. Chuang TJ.
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169	Indentation problems of two-dimensional anisotropic thermoelasticity with perturbed boundaries	Chao CK. Gao B.
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191	The initial post-buckling behavior of face-sheet delaminations in sandwich composites	Kardomateas GA. Huang H.
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227	Transient study of mode iii fracture in an elastic solid with a single plane of material symmetry	Brock LM.
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275	The motion of a rolling polygon	Beunder EM. Rem PC.
281	Forced vibration of cylindrical helical rods subjected to impulsive loads	Temel B. Calim FF.
292	Vibration of thick circular disks and shells of revolution	Singh AV. Subramaniam L.
299	Rocking vibration of rotating disk and spindle systems with asymmetric bearings	Park JS. Shen IY. Ku CPR.
302	Analytically approximate solutions for vibrations of a long discrete chain	Lee W.
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25	Micromechanically based poroelastic modeling of fluid flow in haversian bone	Swan CC. Lakes RS. Brand RA. Stewart KJ.
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49	Transitional flow at the venous anastomosis of an arteriovenous graft: potential activation of the erk1/2 mechanotransduction pathway	Loth F. Fischer PF. Arslan N. Bertram CD. Lee SE. Royston TJ. Shaalan WE. Bassiouny HS.
62	A new automated method for the quantification of mitral regurgitant volume and dynamic regurgitant orifice area based on a normalized centerline velocity distribution using color m-mode and continuous wave doppler imaging	Deserranno D. Greenberg NL. Thomas JD. Garcia MJ.
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78	A 3d biomechanical model of the hand for power grip	Sancho-Bru JL. Perez-Gonzalez A. Vergara M. Giurintano DJ.
84	Experimental verification of the roles of intrinsic matrix viscoelasticity and tension-compression nonlinearity in the biphasic response of cartilage	Huang CY. Soltz MA. Kopacz M. Mow VC. Ateshian GA.
94	Experimentally tractable, pseudo-elastic constitutive law for biomembranes: i. theory	Criscione JC. Sacks MS. Hunter WC.
100	Experimentally tractable, pseudo-elastic constitutive law for biomembranes: ii. application	Criscione JC. Sacks MS. Hunter WC.
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114	The extent and distribution of cell death and matrix damage in impacted chondral explants varies with the presence of underlying bone	Krueger JA. Thisse P. Ewers BJ. Dvoracek-Driksna D. Orth MW. Haut RC.

120	A novel experimental method to estimate stress-strain behavior of intact coronary arteries using intravascular ultrasound (ivus)	Tajaddini A. Kilpatrick DL. Vince DG.
124	Viscoelastic characterization of peripapillary sclera: material properties by quadrant in rabbit and monkey eyes	Downs JC. Suh JKF. Thomas KA. Bellezza AJ. Burgoyne CF. Hart RT.
132	Parameter estimation in a crossbridge muscle model	Lin DC. Nichols TR.
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321	Generating dynamic simulations of movement using computed muscle control	Thelen DG. Anderson FC. Delp SL.
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339	Optical determination of anisotropic material properties of bovine articular cartilage in compression	Wang CCB. Chahine NO. Hung CT. Ateshian GA.
355	Model and influence of mitral valve opening during the left ventricular filling	Baccani B. Domenichini F. Pedrizzetti G.
363	Ligament fibre recruitment and forces for the anterior drawer test at the human ankle joint	Corazza F. O'Connor JJ. Leardini A. Castelli VP.
373	Timing of administration of transforming growth factor-beta and epidermal growth factor influences the effect on material properties of the in situ frozen-thawed anterior cruciate ligament	Azuma H. Yasuda K. Tohyama H. Sakai T. Majima T. Aoki Y. Minami A.
383	Modeling of time-dependent force response of fingertip to dynamic loading	Wu JZ. Dong RG. Smutz WP. Schopper AW.
393	Keep on your toes: gait initiation from toe-standing	Nolan L. Kerrigan DC.
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413	Biomechanical simulations of forward fall arrests: effects of upper extremity arrest strategy, gender and aging-related declines in muscle strength	DeGoede KM. Ashton-Miller JA.
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431	A femoral neck fracture model in rabbits	Ohnishi I. Oikawa K. Tsuji K. Ichikawa T. Kurokawa T.
443	Dynamic measurement of internal solid displacement in articular cartilage using ultrasound backscatter	Fortin M. Buschmann MD. Bertrand MJ. Foster FS. Ophir J.
449	Fiberoptic measurement of tendon forces is influenced by skin movement artifact	Erdemir A. Hamel AJ. Piazza SJ. Sharkey NA.
457	Kinematic modeling of single muscle fiber during diaphragm shortening	Kyckelhahn BA. Nason PB. Tidball JG. Boriek AM.

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473	Rapid neck muscle adaptation alters the head kinematics of aware and unaware subjects undergoing multiple whiplash-like perturbations	Siegmund GP. Sanderson DJ. Myers BS. Inglis JT.
483	In vivo forces used to develop design parameters for tissue engineered implants for rabbit patellar tendon repair	Juncosa N. West JR. Galloway MT. Bolvin GP. Butler DL.
489	Early cement damage around a femoral stem is concentrated at the cement/bone interface	Race A. Miller MA. Ayers DC. Mann KA.
497	Non-linear viscoelastic models predict fingertip pulp force-displacement characteristics during voluntary tapping	Jindrich DL. Zhou YH. Becker T. Dennerlein JT.
505	Correlation between active and passive isometric force and intramuscular pressure in the isolated rabbit tibialis anterior muscle	Davis J. Kaufman KR. Lieber RL.
513	Theories of bipedal walking: an odyssey	Vaughan CL.
525	Effects of elastic property of the wall on flow characteristics through arterial stenoses	Moayeri MS. Zendehbudi GR.
537	Elastohydrodynamic lubrication analysis of metal-on-metal hip-resurfacing prostheses	Udofia IJ. Jin ZM.
545	Optimised performance of the backward longswing on rings	Yeadon MR. Brewin MA.
553	In situ chondrocyte deformation with physiological compression of the feline patellofemoral joint	Clark AL. Barclay LD. Matyas JR. Herzog W.
569	The effect of material characteristics of shoe soles on muscle activation and energy aspects during running	Nigg BM. Stefanyshyn D. Cole G. Stergiou P. Miller J.
577	Kinematics, kinetics, and finite element analysis of commonplace maneuvers at risk for total hip dislocation	Nadzadi ME. Pedersen DR. Yack HJ. Callaghan JJ. Brown TD.
593	New insight into deformation-dependent hydraulic permeability of gels and cartilage, and dynamic behavior of agarose gels in confined compression	Gu WY. Yao H. Huang CY. Cheung HS.
599	Normalization of joint moments during gait: a comparison of two techniques	Moisio KC. Sumner DR. Shott S. Hurwitz DE.
605	A model of fracture testing of soft viscoelastic tissues	Koop BE. Lewis JL.

609	Estimation of discretization errors in contact pressure measurements	Fregly BJ. Sawyer WG.
615	Comment on "a mathematical formula to calculate the theoretical range of motion for total hip arthroplasty"	Widmer KH.
617	Comment on "a mathematical formula to calculate the theoretical range of motion for total hip arthroplasty" - response	Yoshimine F.
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661	Residual strains in conduit arteries	Rachev A. Greenwald SE.
671	Geometrical, functional, and histomorphometric adaptation of rat carotid artery in induced hypertension	Fridez P. Zulliger M. Bobard F. Montorzi G. Miyazaki H. Hayashi K. Stergiopulos N.
681	Shear stress, vascular remodeling and neointimal formation	Wentzel JJ. Gijsen FJH. Stergiopulos N. Serruys PW. Slager CJ. Krams R.
689	Comparison of coronary artery dynamics pre- and post-stenting	Zhu H. Warner JJ. Gehrig TR. Friedman MH.
699	A computational fluid-structure interaction analysis of a fiber-reinforced stentless aortic valve	De Hart J. Baaijens FPT. Peters GWM. Schreurs PJG.
713	Global cardiac function: mechano-energetico-informatics	Suga H.
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111	Damage tolerance of notched composite laminates with reinforcing strips	Qing XL. Chang FK. Starnes J.
129	Viscoelastic characterization of transversely isotropic composite laminae	Melo JDD. Radford DW.
147	Homogenization modeling and effective mechanical constants for em composite conductor with cooling channel	Sun W. Tzeng JT.
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195	Experimental and theoretical analysis of pulling force in pultrusion and resin injection pultrusion (rip) - part ii: modeling and simulation	Li SJ. Xu LQ. Ding ZM. Lee LJ.
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233	Static behavior characteristics of hybrid composites with nonwoven carbon tissue	Lee SH. Noguchi H. Cheong SK.
253	Fatigue behavior characteristics of hybrid composites with nonwoven carbon tissue	Lee SH. Noguchi H. Cheong SK.
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333	Damage mechanism of hybrid composites with nonwoven carbon tissue subjected to quasi-static indentation loads	Lee SH. Aono Y. Noguchi H. Cheong SK.
351	Microstrip antenna for sar application with composite sandwich construction: surface-antenna-structure demonstration	You CS. Hwang W. Park HC. Lee RM. Park WS.
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421	Time-dependent microcracking detected in a rubber-toughened carbon-epoxy composite by the modal acoustic emission method	Bocchieri RT. Schapery RA. Gorman MR.
453	Modified short beam shear test for measurement of interlaminar shear strength of composites	Abali F. Pora A. Shivakumar K.
465	Processing of iron oxide-epoxy vinyl ester nanocomposites	Park SS. Bernet N. de la Roche S. Hahn HT.

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503	Numerical modeling of heat transfer for squeeze casting of mmcs	Jung CK. Jung SW. Nam HW. Han KS.
519	A comparison of oven-cured and induction-cured adhesively bonded composite joints	Mahdi S. Kim HJ. Gama BA. Yarlagadda S. Gillespie JW.
543	Effect of transverse matrix cracks on the relaxation moduli of linear viscoelastic laminates	Noh J. Whitcomb J.
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597	Low cycle fatigue of composite laminates: a damage-mode-sensitive model	Harik VM. Bogetti TA.
611	Impact damage of partially foam-filled co-injected honeycomb core sandwich composites	Vaidya UK. Ulven C. Pillay S. Ricks H.
627	Effects of moisture and temperature on high strain rate behavior of s2-glass-vinyl ester woven-composites	Haque A. Hossain MK.
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715	On modeling bonds in fused, porous networks: 3d simulations of fibrous-particulate joints	Berhan L. Sastry AM.
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549	Analysis of trapped entanglements in polymer networks	Lang M. Michalke W. Kreitmeier S.
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230	Computing unstable manifolds of periodic orbits in delay differential equations	Krauskopf B. Green K.
250	Coarse-grained stochastic processes and monte carlo simulations in lattice systems	Katsoulakis MA. Majda AJ. Vlachos DG.
279	Isod - an anisotropic isovalue-oriented diffusion artificial viscosity for the euler and navier-stokes equations	Remaki L. Beaugendre H. Habashi WG.
295	Numerical investigation of flows in czochralski crystal growth by an axisymmetric lattice boltzmann method	Peng Y. Shu C. Chew YT. Qiu J.
308	Explicit volume-preserving and symplectic integrators for trigonometric polynomial flows	Quispel GRW. McLaren DI.
317	Near-wall les closure based on one-dimensional turbulence modeling	Schmidt RC. Kerstein AR. Wunsch S. Nilsen V.
356	Comment on the article "an effective particle tracing scheme on structured/unstructured grids in hybrid finite volume pdf monte carlo methods" by li and modest	Minier JP. Cao R. Pope SB.
359	Reply to the comment on the article "an effective particle tracing scheme on structured/unstructured grids in hybrid finite volume pdf monte carlo methods" by g. li and m.f. modest [j. comp. phys. 173 (2001) 187-207]	Li G. Modest MF.
360	Self-consistent modeling of turbulence and transport (vol 185, pg 399, 2003)	Shestakov AI. Cohen RH. Crotinger JA. LoDestro LL. Tarditi A. Xu XQ.

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361	Discrete equations for physical and numerical compressible multiphase mixtures	Abgrall R. Saurel R.
397	A three-dimensional spectral element model for the solution of the hydrostatic primitive equations	Iskandarani M. Haidvogel DB. Levin JC.
426	Energy, ropelength, and other physical aspects of equilateral knots	Millett KC. Rawdon EJ.
457	High order numerical methods for the space non-homogeneous boltzmann equation	Filbet F. Russo G.
481	Electromigration of intergranular voids in metal films for microelectronic interconnects	Averbuch A. Israeli M. Ravve I.
503	Unsteady free surface flow simulation over complex topography with a multidimensional upwind technique	Brufau P. Garcia-Navarro P.
527	Generalized random walk algorithm for the numerical modeling of complex diffusion processes	Vamos C. Suciu N. Vereecken H.
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610	Spectral element filtering techniques for large eddy simulation with dynamic estimation	Blackburn HM. Schmidt S.

630	Chebyshev super spectral viscosity method for a fluidized bed model	Sarra SA.
652	A digital filter based generation of inflow data for spatially developing direct numerical or large eddy simulations	Klein A. Sadiki A. Janicka J.
666	Interpolating wavelet collocation method of time dependent maxwell's equations: characterization of electrically large optical waveguide discontinuities	Fujii M. Hoefer WJR.
690	Resolution of high order weno schemes for complicated flow structures	Shi J. Zhang YT. Shu CW.
697	A heap-based algorithm for the study of one-dimensional particle systems	Noullez A. Fanelli D. Aurell E.

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47	Multi-scale finite-volume method for elliptic problems in subsurface flow simulation	Jenny P. Lee SH. Tchelepi HA.
68	Induction heating processes optimization a general optimal control approach	Favennec Y. Labbe V. Bay F.
95	Telescopic projective methods for parabolic differential equations	Gear CW. Kevrekidis IG.
110	A second order coupled level set and volume-of-fluid method for computing growth and collapse of vapor bubbles	Sussman M.
137	Modeling uncertainty in flow simulations via generalized polynomial chaos	Xiu DB. Karniadakis GE.
168	A modified nodal scheme for the time-dependent, incompressible navier-stokes equations	Wang F. Rizwan-uddin.
197	Commutative discrete filtering on unstructured grids based on least-squares techniques	Haselbacher A. Vasilyev OV.
212	A case study of methods of series summation: kelvin-helmholtz instability of finite amplitude	Khan MAH. Tourigny Y. Drazin PG.
230	Ground-state solution of bose-einstein condensate by directly minimizing the energy functional	Bao WZ. Tang WJ.
255	A finite element technique for multifluid incompressible flow using eulerian grids	Minev PD. Chen T. Nandakumar K.
274	Statistical error in particle simulations of hydrodynamic phenomena	Hadjiconstantinou NG. Garcia AL. Bazant MZ. He G.
298	An adaptive n-body algorithm of optimal order	Pruett CD. Rudmin JW. Lacy JM.
318	Numerical solution of the gross-pitaevskii equation for bose-einstein condensation	Bao WZ. Jaksch D. Markowich PA.
343	Symmetry-preserving discretization of turbulent flow	Verstappen RWCP. Veldman AEP.
369	A spectral/b-spline method for the navier-stokes equations in unbounded domains (vol 185, pg 532, 2003)	Dufresne L. Dumas G.

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1	Basic issues concerning finite strain measures and isotropic stress-deformation relations	Xiao H. Bruhns OT. Meyers A.
25	On cavitation, configurational forces and implications for fracture in a nonlinearly elastic material	Sivaloganathan J. Spector SJ.
51	Equivalence between the local boundary integral equation and the mean value theorem in the theory of elasticity	Wang MZ. Sun SL.
61	Elastic materials with two stress-free configurations	Abeyaratne R. Knowles JK.

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90	Investigation of nanomechanical properties of the interphase in a glass fiber reinforced polyester composite using nanoindentation	Khanna SK. Ranganathan P. Yedla SB. Winter RM. Paruchuri K.
97	Modeling of fatigue crack propagation during sliding wear of polymers	Sadeghipour K. Baran G. Zhang HQ. Wu W.
107	On the improvement of calibration coefficients for hole-drilling integral method: part ii - experimental validation of calibration coefficients	Aoh JN. Wei CS.
116	Simulating distortion and residual stresses in carburized thin strips	Prantil VC. Callabresi ML. Lathrop JF. Ramaswamy GS. Lusk MT.
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133	Analysis of tube free hydroforming using an inverse approach with fld-based adjustment of process parameters	Nguyen BN. Johnson KI. Khaleel MA.
141	Experimental implementation of neural network springback control for sheet metal forming	Viswanathan V. Kinsey B. Cao J.
148	Optimization of directionally attached piezoelectric actuators	Wetherhold R. Messer M. Patra A.

153	Measurement of in-plane residual stresses varying with depth by the interferometric strain/slope rosette and incremental hole-drilling	Tjhung T. Li KY.
163	Surface enhancement of al2o3 fiber with nanosized al2o3 particles using a dry mechanical coating process	Coowanitwong N. Wu CY. Nguyen J. Cai M. Ruthkosky M. Rogers J. Feng L. Watano S. Yoshida T.
170	An approximate method of estimating the yield of a strip under tension cut by serrated surfaces on opposite faces	Shi JY. McElwain DLS. Domanti SA.
176	Determination of interface fracture toughness in thermal barrier coating system by blister tests	Zhou YC. Hashida T. Jian CY.
183	A closure, model to crack growth under large-scale yielding and through residual, stress fields	Wang CH. Barter SA. Liu Q.
191	Constitutive modeling of cold compaction and sintering of hardmetal	Mahler L. Runesson K.
200	Implementation of a viscoplastic model for a plasma sprayed ceramic thermal barrier coating	Xie WG. Walker KP. Jordan EH. Gell M.
208	New estimation method of fatigue properties of aluminum alloys	Park JH. Song JH.
215	Plastic collapse of cylinders under constrained conditions	Abdul-Latif A. Nesnas K.
222	Numerical simulation of residual stresses in a spot welded joint	Long X. Khanna SK.
227	Dynamic fracture toughness and charpy transition properties of a service-exposed 2.25cr-1mo reheater header pipe	Sreenivasan PR. Shastry CG. Mathew MD. Rao KBS. Mannan SL. Bandyopadhyay G.

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269	Mathematical analysis of viscometric (polymer) flow fields in capillaries: taylor dispersion revisited	Cook LP. Nwankwo E. Schleiniger G. Wood B.
283	Surface-tension-driven flow on a moving curved surface	Howell PD.
309	Fluid motion for car undertrays in ground effect	Jones MA. Smith FT.
335	Nondiffusive hot spot in a confined, narrow domain	Kapila AK. Short M.
367	The effect of a retarder on the early stages of the hydration of tricalcium silicate	Salhan A. Billingham J. King AC.
379	Intermediate asymptotics for richards' equation in a finite layer	Witelski TP.

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33	Radiation of sound waves from a rigid stepped cylindrical waveguide	Turetken B. Buyukaksoy A. Demir A.
55	Propagation of strong converging shock waves in a gas of variable density	Madhumita G. Sharma VD.
69	Numerical simulation of an elastoplastic plate via mixed finite elements	Della Croce L. Venini P. Nascimbene R.
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373	Micromechanical modeling of filament wound cement-based composites	Mobasher B.
383	Numerical modeling of coupled hygromechanical degradation of cementitious materials	Meschke G. Grasberger S.
393	Scale transition in steel-concrete interaction. i: model	Lackner R. Mang HA.
403	Scale transition in steel-concrete interaction. ii: applications	Lackner R. Mang HA.
414	Postbuckling of pressure-loaded functionally graded cylindrical panels in thermal environments	Shen HS. Leung AYT.
426	Modeling water and sulfuric acid transport through coated cement concrete	Liu J. Vipulanandan C.
438	Postbuckling analysis of plates resting on a tensionless elastic foundation	de Holanda AS. Goncalves PB.
449	Random uncertainties model in dynamic substructuring using a nonparametric probabilistic model	Soize C. Chebli H.
458	Considerations of multimode structural response for near-field earthquakes	Huang CT.
468	Stability criteria for euler columns with intermediate and end axial loads	Wang CM. Wang CY. Nazmul IM.
473	Discussion of "analysis of shear banding in true triaxial tests on sand" by poul v. lade and qiong wang	Cela JJL.
474	Closure to "analysis of shear banding in true triaxial tests on sand" by poul v. lade and qiong wang	Lade PV. Wang Q.

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489	Constructing second-order models of mechanical systems from identified state space realizations. part ii: numerical investigations	Lus H. De Angelis M. Betti R. Longman RW.
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514	Control of wind-induced self-excited oscillations by transfer of internal energy to higher modes of vibration. i: analysis in two degrees of freedom	Le Diouron T. Fujino Y. Abe M.
526	Control of wind-induced self-excited oscillations by transfer of internal energy to higher modes of vibration. ii: application to taut cables	Le Diouron T. Fujino Y. Abe M.
539	Smooth convex three-dimensional particle for the discrete-element method	Kuhn MR.
548	Inelastic cyclic model for steel braces	Jin J. El-Tawil S.
558	Numerical solution of fully developed flow with vegetative resistance	Neary VS.
564	Hybrid beam-column element with end frictional joints	Law SS. Wu ZM. Chan SL.
571	Damage detection in concrete by fourier and wavelet analyses	Melhem H. Kim HS.
578	Stability of periodically unsteady axisymmetric jet	Carrara MD. Hajj MR.
581	Discussion of ”numerical investigation of fiber reinforced polymers poststrengthened concrete slabs” by matthias hormann, horst menrath, and ekkehard ramm	Pfeiffer U. Quast U.
583	Closure to ”numerical investigation of fiber reinforced polymers poststrengthened concrete slabs” by matthias hormann, horst menrath, and ekkehard ramm	Hormann M. Menrath H. Ramm E.

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1	Coherent structures in oscillatory boundary layers	Costamagna P. Vittori G. Blondeaux P.
35	Experimental study of the instability of unequal-strength counter-rotating vortex pairs	Ortega JM. Bristol RL. Savas O.
85	Strong solitary internal waves in a 2.5-layer model	Voronovich AG.
95	Effects of solute mass transfer on the stability of capillary jets	Collantes GO. Yariv E. Frankel I.
117	The flow field and bare-spot formation in spin-up from rest of a two-layer fluid about a vertical axis	Ungarish M. Mang J.
147	The motion of a fluid ellipsoid in a general linear background flow	McKiver WJ. Dritschel DG.
175	The shape of vortices in quasi-geostrophic turbulence	Reinaud JN. Dritschel DG. Koudella CR.
193	Micro-structure and lagrangian statistics of the scalar field with a mean gradient in isotropic turbulence	Brethouwer G. Hunt JCR. Nieuwstadt FTM.
227	On gravity-driven flow through a reacting porous rock	Raw AWV. Woods AW.
245	The nonlinear evolution of zonally symmetric equatorial inertial instability	Griffiths SD.
275	Mathematical modelling of the overflowing cylinder experiment	Howell PD. Breward CJW.
299	Nonlinear dynamics over rough topography: homogeneous and stratified quasi-geostrophic theory	Vanneste J.
319	Computation of the pressure inside bubbles and pores in stokes flow	Pozrikidis C.
339	Frictional two-layer exchange flow	Zaremba LJ. Lawrence GA. Pieters R.
355	Statistical structure of high-reynolds-number turbulence close to the free surface of an open-channel flow	Calmet I. Magnaudet J.
379	The unsteady karman problem for a dilute particle suspension	Foster MR. Duck PW. Hewitt RE.

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41	The physical mechanism for vortex merging	Cerretelli C. Williamson CHK.
79	Tsunami run-up and draw-down on a plane beach	Carrier GF. Wu TT. Yeh H.
101	The mixing layer over a deep cavity at high-subsonic speed	Forestier N. Jacquin L. Geffroy P.
147	Amplitude growth rate of a richtmyer-meshkov unstable two-dimensional interface to intermediate times	Zabusky NJ. Kotelnikov AD. Gulak Y. Peng GZ.
163	Hydraulic control of homogeneous shear flows	Garrett C. Gerdes F.
173	Mixed velocity-passive scalar statistics in high-reynolds-number turbulence	Mydlarski L.
205	Non-isothermal dispersed phase of particles in turbulent flow	Pandya RVR. Mashayek F.
247	Weakly nonlinear surface waves over a random seabed	Mei CC. Hancock MJ.
269	Sound radiation in turbulent channel flows	Hu ZW. Morfey CL. Sandham ND.
303	Instability of quasi-geostrophic vortices in a two-layer ocean with a thin upper layer	Benilov ES.
333	Modelling the motion of particles around choanoflagellates	Orme BAA. Blake JR. Otto SR.
357	Dynamics of target patterns in low-prandtl-number convection	Siggers JH.
377	Marangoni instability of a thin liquid film heated from below by a local heat source	Kalliadasis S. Kiyashko A. Demekhin EA.

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1	Vibration-induced drop atomization and bursting	James AJ. Vukasinovic B. Smith MK. Glezer A.
29	Vibration-induced drop atomization and the numerical simulation of low-frequency single-droplet ejection	James AJ. Smith MK. Glezer A.
63	On euclidean invariance of algebraic reynolds stress models in turbulence	Weis J. Hutter K.
69	Rheology of bidisperse granular mixtures via event-driven simulations	Alam M. Luding S.
105	Scale-by-scale budget and similarity laws for shear turbulence	Casciola CM. Gualtieri P. Benzi R. Piva R.
115	Drag, deformation and lateral migration of a buoyant drop moving near a wall	Magnaudet J. Takagi S. Legendre D.
159	On steady stokes flow in a trihedral rectangular corner	Gomilko AM. Malyuga VS. Meleshko VV.
179	Direct initiation of detonation with a multi-step reaction scheme	Ng HD. Lee JHS.
213	How vortices mix	Meunier P. Villermaux E.
223	Flow along streamwise corners revisited	Ridha A.
267	Detonation ignition from a temperature gradient for a two-step chain-branching kinetics model	Sharpe GJ. Short M.
293	The effect of base flow variation on flow stability	Bottaro A. Corbett P. Luchini P.
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335	Transient dynamics at the onset of taylor vortices	Abshagen J. Meincke O. Pfister G. Cliffe KA. Mullin T.
345	Compressible bubbles in stokes flow	Crowdy DG.
357	Elliptic and triangular instabilities in rotating cylinders	Eloy C. Le Gal P. Le Dizes S.
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19	Numerical experiments on strongly turbulent thermal convection in a slender cylindrical cell	Verzicco R. Camussi R.
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89	Green's functions for a source in a mixing layer: direct waves, refracted arrival waves and instability waves	Suzuki T. Lele SK.
129	Green's functions for a source in a boundary layer: direct waves, channelled waves and diffracted waves	Suzuki T. Lele SK.
175	The stability of ink-jet printed lines of liquid with zero receding contact angle on a homogeneous substrate	Duineveld PC.
201	Rotational and orientational behaviour of three-dimensional spheroidal particles in couette flows	Qi DW. Luo LS.
215	A large-eddy simulation study of transition and flow instability in a porous-walled chamber with mass injection	Apte SV. Yang V.
227	The nonlinear instability of thread-annular flow at high reynolds number	Walton AG.
259	Internal wave resonances in strain flows	Leblanc S.
285	Accuracy and convergence of velocity formulations for water waves in the framework of boussinesq theory	Madsen PA. Agnon Y.
321	Quasi-static solutions for quantum vortex motion under the localized induction approximation	Lipniacki T.
339	The kelvin-helmholtz to holmboe instability transition in stratified exchange flows	Hogg AM. Ivey GN.
363	Improved upper bound on the energy dissipation rate in plane couette flow: the full solution to busse's problem and the constantin-doering-hopf problem with one-dimensional background field	Plasting SC. Kerswell RR.
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11	Turbulence over a compliant surface: numerical simulation and analysis	Xu S. Rempfer D. Lumley J.
35	Characteristics of vortex packets in turbulent boundary layers	Ganapathisubramani B. Longmire EK. Marusic I.
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81	Shoaling solitary internal waves: on a criterion for the formation of waves with trapped cores	Lamb KG.
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135	Three-dimensional acoustic-roughness receptivity of a boundary layer on an airfoil: experiment and direct numerical simulations	Wurz W. Herr S. Worner A. Rist U. Wagner S. Kachanov YS.
165	The influence of non-equilibrium surfactant dynamics on the flow of a semi-infinite bubble in a rigid cylindrical capillary tube	Ghadiali SN. Gaver DP.
197	Spatio-temporal dynamics of a periodically driven cavity flow	Vogel MJ. Hirsa AH. Lopez JM.
227	Intermittency in solutions of the three-dimensional navier-stokes equations	Gibbon JD. Doering CR.
237	Vorticity production in shock diffraction	Sun M. Takayama K.
257	Large-scale structures in a developed flow over a wavy wall	Gunther A. von Rohr PR.
287	Laminar starting plumes in high-prandtl-number fluids	Kaminski E. Jaupart C.
299	Particle image velocimetry and visualization of natural and forced flow around rectangular cylinders	Mills R. Sheridan J. Hourigan K.
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39	Propagation laws for steady curved detonations with chain-branching kinetics	Short M. Bdzil JB.
65	The effect of surface tension on rimming flows in a partially filled rotating cylinder	Ashmore J. Hosoi AE. Stone HA.
99	Stabilization of a hypersonic boundary layer using an ultrasonically absorptive coating	Fedorov A. Shiplyuk A. Maslov A. Burov E. Malmuth N.
125	Pattern formation in the marginally unstable ekman layer	Haeusser TM. Leibovich S.
145	On internal fronts	Dias F. Vanden-Broeck JM.
155	Three-dimensional instability and vorticity patterns in the wake of a flat plate	Julien S. Lasheras J. Chomaz JM.
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199	An improved exact riemann solver for multi-dimensional relativistic flows	Rezzolla L. Zanotti O. Pons JA.
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231	What happens to pressure when a flow enters a side branch?	Smith FT. Ovenden NC. Franke PT. Doorly DJ.
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287	The motion of solids in inviscid uniform vortical fields	Miloh T.
307	Marangoni flotation of liquid droplets	Savino R. Paterna D. Lappa M.
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25	Closed-form linear stability conditions for rotating rayleigh-benard convection with rigid stress-free upper and lower boundaries	Kloosterziel RC. Carnevale GF.
43	Cavitation luminescence from flow over a hydrofoil in a cavitation tunnel	Leighton TG. Farhat M. Field JE. Avellan F.
61	Minimum dissipation rate flow with given flux	Keller JB.
65	Stability of symmetric vortices in two dimensions and over three-dimensional slender conical bodies	Cai JS. Liu F. Luo SJ.
95	Rheology of suspensions with high particle inertia and moderate fluid inertia	Wylie JJ. Koch DL. Ladd AJC.
119	Particle-laden tubeless siphon	Wang J. Joseph DD.
129	Decaying turbulence in an active-grid-generated flow and comparisons with large-eddy simulation	Kang HS. Chester S. Meneveau C.
161	A direct stability analysis of a radiation-induced natural convection boundary layer in a shallow wedge	Lei CW. Patterson JC.
185	Magnetic stabilization of the buoyant convection between infinite horizontal walls with a horizontal temperature gradient	Kaddeche S. Henry D. Benhadid H.
217	On the interaction of a vertical shear layer with a free surface	Dabiri D.
233	Integral methods for shallow free-surface flows with separation	Watanabe S. Putkaradze V. Bohr T.
267	Viscous fingering with chemical reaction: effect of in-situ production of surfactants	Fernandez J. Homsy GM.
283	Effect of deceleration on jet instability	Shtern V. Hussain F.
311	On the dynamics of the collapse of a diffusion-flame hole	Pantano C. Pullin DI.
333	Stability of thermocapillary flows in non-cylindrical liquid bridges (vol 458, pg 35, 2002)	Nienhuser C. Kuhlmann HC.

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1	Estimation of the flutter derivatives of an naca airfoil by means of navier-stokes simulation	Le Maitre OP. Scanlan RH. Knio OM.
29	Numerical investigation of transonic limit cycle oscillations of a two-dimensional supercritical wing	Tang L. Bartels RE. Chen PC. Liu DD.
43	An experimental investigation of unsteady turbulent-wake/boundary-layer interaction	Gete Z. Evans RL.
57	Fluctuating lift on a circular cylinder: review and new measurements [review]	Norberg C.
97	Flow/acoustic interactions of two cylinders in cross-flow	Fitzpatrick JA.
115	The added mass of a flexible plate oscillating in a fluid	Yadykin Y. Tenetov V. Levin D.
125	A fluid-beam model for flow in a collapsible channel	Cai ZX. Luo XY.
147	Modal expansion of the perturbation velocity potential for a cantilevered fluid-conveying cylindrical shell	Langthjem MA. Olhoff N.
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225	Flutter and limit cycle oscillations of two-dimensional panels in three-dimensional axial flow	Tang DM. Yamamoto H. Dowell EH.
243	A theoretical and experimental investigation of the effects of a steady angle of attack on the nonlinear flutter of a delta wing plate model	Attar PJ. Dowell EH. Tang DM.
261	Near-wake vortex motions behind a circular cylinder at low reynolds number	Sung J. Yoo JY.
275	Energy distribution from vertical impact of a three-dimensional solid body onto the flat free surface of an ideal fluid	Scolan YM. Korobkin AA.
287	Booming and singing acoustic emissions from fluidized granular beds	Patitsas AJ.
317	Multisolitons on vortex filaments: the origin of axial tangling	Maksimovic A. Lugomer S. Michieli I.
331	Investigation of peak frequencies in the flopping regime with a two-cylinder array	Guillaume DW. LaRue JC.
337	Controlled oscillations of a cylinder: a new wake state	Carberry J. Sheridan J. Rockwell D.

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345	Some vortex-shedding characteristics of the staggered configuration of circular cylinders	Sumner D. Richards MD.
351	Scaling of damping induced by bubbly flow across tubes	Baj F. de Langre E.
365	Flow-induced force fluctuations on a sphere at high strouhal number	Wang J. Lauchle GC. Howe MS.
381	Shallow cavity flow tone experiments: onset of locked-on states	Rockwell D. Lin JC. Oshkai P. Reiss M. Pollack M.
415	Nonlinear statics and dynamics of a simply supported nonuniform tube conveying an incompressible inviscid fluid	Sorokin SV. Terentiev AV.
433	On the bifurcations of a rigid rotor response in squeeze-film dampers	Inayat-Hussain JI. Kanki H. Mureithi NW.
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479	A note on the fluid damping of an elastic cylinder in a cross-flow	Zhang HJ. Zhou Y. So RMC. Mignolet MP. Wang ZJ.
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239	Modeling and qualitative experiments on swirling bubbly flows: single bubble with rossby number of order 1	Magaud F. Najafi AF. Angilella JR. Souhar M.
247	Simulation of swirling gas-particle flows using different time scales for the closure of two-phase velocity correlation in the second-order moment two-phase turbulence model	Yu Y. Zhou LX. Zheng CG. Liu ZH.
251	Effect of unsteady wake passing frequency on boundary layer transition, experimental investigation, and wavelet analysis	Schobeiri MT. Read K. Lewalle J.
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275	An experimental investigation of starting impinging jets	Lai HZ. Naughton JW. Lindberg WR.
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409	Impact of droplets of magneto-rheological suspension under applied magnetic fields	Sudo S. Funaoka M. Nishiyama H.
415	Lyapunov-based control of a bridge using magneto-rheological fluid dampers	Wang XJ. Gordaninejad F.
421	Vibration isolation of structural systems using squeeze mode er mounts	Hong SR. Choi SB. Jung WJ. Jeong WB.
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509	Electrorheological semi-active damper: polyaniline based er system	Kim JW. Cho YH. Choi HJ. Lee HG. Choi SB.
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521	Semiactive vibration control of a smart seat with an mr fluid damper considering its time delay	Park CH. Jeon DY.
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365	Discussion on the local flexibility due to the crack in a cracked rotor system	Zou J. Chen J. Niu JC. Geng ZM.

370	Comments on "free vibration analysis of arbitrarily shaped plates with clamped edges using wave-type function"	Chen JT. Chen IL. Chen KH. Lee YT.
379	Comments on "free vibration analysis of arbitrarily shaped plates with clamped edges using wave-type function" - author's reply	Kang SW. Lee JM.

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381	2001 india-usa symposium on emerging trends in vibration and noise engineering columbus, oh, usa, 10-12 december 2001 - foreword	Soedel W.
391	Flexible polyurethane foam modelling and identification of viscoelastic parameters for automotive seating applications	Deng R. Davies P. Bajaj AK.
419	Examination of multi-dimensional vibration isolation measures and their correlation to sound radiation over a broad frequency range	Singh R. Kim S.
457	Recent applications of viscoelastic damping for noise control in automobiles and commercial airplanes	Rao MD.
475	A study of damping in fiber-reinforced composites	Chandra R. Singh SP. Gupta K.
497	Analysis and design of pod silencers	Munjal ML.
509	Acoustic attenuation of hybrid silencers	Selamet A. Lee IJ. Huff NT.
529	Finite element modelling of piezolaminated smart structures for active vibration control with distributed sensors and actuators	Narayanan S. Balamurugan V.
563	Efficient modal control strategies for active control of vibrations	Singh SP. Pruthi HS. Agarwal VP.
577	Active control of cylindrical shell with magnetostrictive layer	Kumar JS. Ganesan N. Swarnamani S. Padmanabhan C.
591	Equilibrium point damage prognosis models for structural health monitoring	Brown RL. Adams DE.
613	Stochastic dynamics of parametrically excited two d.o.f. systems with symmetry	Namachchivaya NS. Ramakrishnan N.
633	Model reduction for parametric instability analysis in shells conveying fluid	Kochupillai J. Ganesan N. Padmanabhan C.
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677	Application of a generalized residual model to frequency domain modal parameter estimation	Fladung WA. Phillips AW. Allemang RJ.
707	A survey of dsp methods for rotating machinery analysis, what is needed, what is available	Blough JR.
721	Chatter recognition by a statistical evaluation of the synchronously sampled audio signal	Schmitz TL.
731	Turbomachine blade damping	Rao JS. Saldanha A.
739	Structural vibration suppression via active/passive techniques	Garg DP. Anderson GL.
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865	Application of the green functions to the problem of the thermally induced vibration of a beam	Kidawa-Kukla J.
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907	Identification of a continuous structure with a geometrical non-linearity. part ii: proper orthogonal decomposition	Lenaerts V. Kerschen G. Golinval JC.
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989	Comparison of higher order versions of the method of multiple scales for an odd non-linearity problem	Pakdemirli M.
999	Experimental study on stability of an mr fluid damper-rotor-journal bearing system	Wang J. Meng G.

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95	Modelling plasticity using strain nuclei: discretization of the dislocation field by uniform, triangles	McKellar DK. Hills DA. Sackfield A.
103	Theoretical stress concentration factors for short shouldered plates subjected to uniform tension	Troyani N. Marin A. Garcia H. Rodriguez F. Rodriguez S. Gomes C.
115	A self-powered damage detection sensor	Elvin N. Elvin A. Choi DH.
125	Interpretation of damage mechanics behaviour of two-bar structures for the life extension of high-temperature components	Tu ST. Ling X.
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161	Computation of stresses and deformations for a two-dimensional sliding contact between an elastic layer and a rigid indenter with a rounded profile	Jaffar MJ.
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607	An examination of the competition between bulk behavior and interfacial behavior of ceramics subjected to dynamic pressure-shear loading	Zavattieri PD. Espinosa HD.
637	Grain boundary versus transgranular ductile failure	Pardoen T. Dumont D. Deschamps A. Brechet Y.
667	Study of particle rearrangement during powder compaction by the discrete element method	Martin CL. Bouvard D. Shima S.
695	Discrete dislocation simulations of the development of a continuum plastic zone ahead of a stationary mode iii crack	Zacharopoulos N. Srolovitz DJ. LeSar R.
715	Slip-line modeling of machining with a rounded-edge tool - part i: new model and theory	Fang N.
743	Slip-line modeling of machining with a rounded-edge tool - part ii: analysis of the size effect and the shear strain-rate	Fang N.
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795	Energy dissipation mechanisms in ductile fracture	Kysar JW.
825	On the computation of the near-tip stress intensities for three-dimensional wedges via two-state m-integral	Lee Y. Im S.
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901	Atomistic simulations of elastic deformation and dislocation nucleation during nanoindentation	Lilleodden ET. Zimmerman JA. Foiles SM. Nix WD.
921	Interfacial cracks between piezoelectric and elastic materials under in-plane electric loading	Liu M. Hsia KJ.
945	Interacting cracks and ellipsoidal inhomogeneities by the equivalent inclusion method	Shodja HM. Rad IZ. Soheilifard R.
961	Diffusive shrinkage of a void within a grian of a stressed polycrystal	Wang H. Li ZH.
977	Electrically driven cracks in piezoelectric ceramics: experiments and fracture mechanics analysis (vol 50, pg 2333, 2002)	dos Santos e Lucato SL. Bahr HA. Pham VB. Lupascu DC. Balke H. Rodel J. Bahr U.

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1059	Size-dependent elastic properties of a single-walled carbon nanotube via a molecular mechanics model	Chang TC. Gao HJ.

1075	Boundary-layer corrections for stress and strain fields in randomly heterogeneous materials	Luciano R. Willis JR.
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1127	Finite thermoelasticity with limiting chain extensibility	Horgan CO. Saccomandi G.
1147	Theoretical development and experimental validation of a thermally dissipative cohesive zone model for dynamic fracture of amorphous polymers	Bjerke TW. Lambros J.

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353	Generalized plane strain thermopiezoelectric analysis of multilayered plates	Vel SS. Batra RC.
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423	Thermal buckling for local delamination near the surface of laminated cylindrical shells and delaminated growth	Wang X. Dai HL.
443	Transient stress intensity factors for periodic array of cracks in a half-plane due to convective cooling	Rizk AEFA.
457	Thermal stresses in a one-sided bonded repair by a plate inclusion model	Duong CN. Yu J.
467	Vibrations of a crystal plate under a thermal bias	Yang JS. Zhang X.
479	Design optimization for structural thermal buckling	Chen BS. Gu YX. Zhao GZ. Lin W. Chang TYP. Kuang JS.

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187	Time domain identification of moving loads on bridge deck	Zhu XQ. Law SS.
199	Identification of nonlinear systems through time-frequency filtering technique	Wang LL. Zhang JH. Wang C. Hu SY.
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31	A study on homogeneous charge compression ignition gasoline engines	Kaneko M. Morikawa K. Itoh J. Saishu Y.
37	Numerical prediction of mixture formation and combustion processes in premixed compression ignition engines	Takeuchi S. Wakisaka T. Kato N. Nguyen TT. Okude K. Isshiki Y.
44	Numerical analysis of the interaction between thermo-fluid dynamics and auto-ignition reaction in spark ignition engines	Saijyo K. Nishiwaki K. Yoshihara Y.
52	Numerical analysis of autoignition and combustion of n-butane and air mixture in homogeneous-charge compression-ignition engine using elementary reactions	Yamasaki Y. Iida N.
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633	Residual stress in plasma sprayed zirconia on cylindrical components	Fogarassy P. Turquier F. Lodini A.
641	Analysis of crack propagation in double cantilever beam tests of multidirectional laminates	de Morais AB. de Moura MF. Goncalves JPM. Camanho PP.
653	An investigation into the effect of carbon on the kinetics of dynamic restoration and flow behavior of carbon steels	Serajzadeh S. Taheri AK.
661	The co-operative role of voids and shear bands in strain localization during bending	Lievers WB. Pilkey AK. Worswick MJ.
675	Using a micromechanical finite element parametric study to motivate a phenomenological macroscale model for void/crack nucleation in aluminum with a hard second phase	Horstemeyer MF. Ramaswamy S. Negrete M.
689	Dynamic loading of polycrystalline shape memory alloy rods	Lagoudas DC. Ravi-Chandar K. Sarh K. Popov P.

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101	Homogenized constitutive equations for linear viscoelastic unidirectional composites with growing transverse cracks	Schapery RA.
133	Time-dependent compressive strength of unidirectional viscoelastic composite materials	Violette MG. Schapery RA.
147	On numerical simulation of cyclic viscoplastic and viscoelastic constitutive laws with the large time increment method	Stehly M. Remond Y.
171	Time-dependent behavior of ceramic (zirconia)-metal (nicocraly) particulate composites	Rangaraj S. Kokini K.
193	Thermal relaxation and high temperature creep of zr(5)5cu(3)0al(10)ni(5) bulk metallic glass	Daniel BSS. Reger-Leonhard A. Heilmaier M. Eckert J. Schultz L.

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207	The non-linear viscoelastic response of polycarbonate in torsion: an investigation of time-temperature and time-strain superposition	O'Connell PA. McKenna GB.
231	Nonlinearly viscoelastic behavior of polycarbonate. i. response under pure shear	Knauss WG. Zhu W.
271	The influence of superimposed creep loadings on the thermal-mechanical fatigue behaviour of the ni-base superalloy in792cc	Beck T. Lang KH. Pitz G. Lohe D.
283	Rheology-structure relationship of polymer/layered silicate hybrids	Kotsilkova R.

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301	Nonlinearly viscoelastic behavior of polycarbonate. ii. the role of volumetric strain	Knauss WG. Zhu W.
323	Parameter-estimation algorithms for characterizing a class of isotropic and anisotropic viscoplastic material models	Saleeb AF. Gendy AS. Wilt TE.
363	An evaluation of linear cumulative damage (miner's law) using kinetic crack growth theory	Christensen RM.

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109	A thermodynamic approach with internal variables using lagrange formalism. part i: general framework	Rahouadj R. Ganghoffer JF. Cunat C.
119	A thermodynamic approach with internal variables using lagrange formalism. part ii. continuous symmetries in the case of the time-temperature equivalence	Rahouadj R. Ganghoffer JF. Cunat C.
125	A novel internal dissipation inequality by isotropy and its implication for inelastic constitutive characterization	Lin RC. Schomburg U.

135	Precise control for vibration of rigid-flexible mechanical arm	Deng ZC. Wang XR. Zhao YL.
143	The lowest order solution of the crack-inhomogeneity interaction for mode i crack	Yang LH. Li ZH.
151	A mode iii crack in functionally graded piezoelectric materials	Wang BL.
161	A new concept of modal participation factor for numerical instability in the dual bem for exterior acoustics	Chen JT. Chen KH. Chen IL. Liu LW.
175	Shear deformation in thermal bending analysis of laminated plates by the gdq method	Hong CC. Jane KC.
187	Dynamic stability analysis of beams on two-parameter elastic soil subjected to partially tangential forces	De Rosa MA. Colangelo F. Messina A.
193	The solution of navier equations of classical elasticity using lie symmetry groups	Ozer T.
203	Two new exactly, solvable cases of the euler-poisson equations	Gao PY.

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209	Non-integrability of anisotropic quasi-homogeneous hamiltonian systems	Arribas M. Elipe A. Riaguas A.
217	Stability and bifurcation in an electromechanical system with time delays	Ji JC.
227	On certain bounds for the in-plane translational stiffness of a disc inclusion at a bi-material elastic interface	Selvadurai APS.
235	Continua with self-rotation nuclei: evolution of asymmetric fields	Teisseyre R. Boratnyski W.
241	Explicit expression of derivatives of elastic green's functions for general anisotropic materials	Lee VG.
251	A constitutive theory for creep behavior of initially isotropic materials sustaining unilateral damage	Betten J. Sklepus A. Zolochevsky A.
257	Controlling the stress-strain inhomogeneities in axially sheared and radially heated hollow rubber tubes via functional grading	Bilgili E.
267	Domain switching effect on fracture of piezoelectric solids	Zeng WJ. Manzari MT. Lee JD. Shen YL.

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169	3-d computer visualization and animation of medical images	Leader JK.
171	Lumbar spine visualisation based on kinematic analysis from videofluoroscopic imaging	Zheng Y. Nixon MS. Allen R.
181	Analysis of the tmj intraarticular space variation: a non-invasive insight during mastication	Fushima K. Gallo LM. Krebs M. Palla S.
191	Relation of jaw sounds and kinematics visualized and quantified using 3-d computer animation	Leader JK. Boston JR. Rudy TE. Greco CM. Zaki HS.
201	Graphic-based musculoskeletal model for biomechanical analyses and animation	Chao EYS.
213	Data representation for joint kinematics simulation of the lower limb within an educational context	Jan SVS. Hilal I. Salvia P. Sholukha V. Poulet P. Kirokoya I. Rooze M.
221	Effect of specimen length: are the mechanics of individual motion segments comparable in functional spinal units and multisegment specimens?	Dickey JP. Kerr DJ.
229	Umbilical flow distribution to the liver and the ductus venosus in human fetuses during gestation: an anatomy-based mathematical modeling	Pennati G. Corno C. Costantino ML. Bellotti M.
239	An implantable device for stimulation of denervated muscles in rats	Dennis RG. Dow DE. Faulkner JA.
255	A medical needle drive for the study of interstitial implant mechanics	Lefrancois R. Sloboda RS.

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275	Biomechanical investigation of pedicle screw-vertebrae complex: a finite element approach using bonded and contact interface conditions	Chen SI. Lin RM. Chang CH.
283	How to determine the permeability for cement infiltration of osteoporotic cancellous bone	Baroud G. Wu JZ. Bohner M. Sponagel S. Steffen T.
289	A method for in-vivo analysis for regional arterial wall material property alterations with atherosclerosis: preliminary results	Chandran KB. Mun JH. Choi KK. Chen JS. Hamilton A. Nagaraj A. McPherson DD.
299	Flow changes in the aorta associated with the deployment of a aaa stent graft	Walsh PW. Chin-Quee S. Moore JE.
309	Lung function interpolation by analysis of means of neural-network-supported respiration sounds	Oud M.
317	Arm emg during abduction and adduction: hysteresis cycle	Politti JC. Felice CJ. Valentinuzzi ME.
321	Prediction of response to incision using the mutual information of electroencephalograms during anaesthesia	Huang L. Yu P. Ju F. Cheng J.

329	Dual channel light pulse exposure timer	Clarkson DM.
335	An experimental two degrees-of-freedom actuated external fixator for in vivo investigation of fracture healing	Bishop NE. Schneider E. Ito K.
341	Development and evaluation of an automated stainer for acid-fast bacilli	Kim SC. Kang SI. Kim DW. Cho SN. Hwang JH. Kim Y. Song SD. Kim YH.

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257	Optimal control of deployment of a tethered subsatellite	Steindl A. Troger H.
275	Suppressing flow-induced vibrations by parametric excitation	Fatimah S. Verhulst F.
299	Hopf bifurcation on a two-neuron system with distributed delays: a frequency domain approach	Liao XF. Li SW. Wong KW.
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367	2 : 2 : 1 resonance in the quasiperiodic mathieu equation	Rand R. Guennoun K. Belhaq M.
375	Derivation and consideration of governing equations of the envelope surface created by directional, nearly monochromatic waves	Nohara BT.
393	Homoclinic tubes in discrete nonlinear schrodinger equation under hamiltonian perturbations	Li YG.
435	Limit cycle oscillation and orbital stability in aeroelastic systems with torsional nonlinearity	Singh SN. Brenner M.

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1	Equivalent linearization and monte carlo simulation in stochastic dynamics [review]	Proppe C. Pradlwarter HJ. Schueller GI.
17	Maximum entropy pdfs and the moment problem under near-gaussian conditions	Volpe EV. Baganoff D.
31	Response spectral density of linear systems with external and parametric non-gaussian, delta-correlated excitation	Iourtchenko DV.
37	Parallel processing in computational stochastic dynamics	Johnson EA. Proppe C. Spencer BF. Bergman LA. Szekely GS. Schueller GI.
61	A study of damping errors in correlation-driven stochastic realizations using short data sets	Pridham BA. Wilson JC.
79	Non-linear stochastic control via stationary response design	Crespo LG. Sun JQ.
87	A monte carlo simulation model for stationary non-gaussian processes	Grigoriu A. Ditlevsen O. Arwade SR.

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539	The 'indian wire trick' via parametric excitation: a comparison between theory and experiment	Mullin T. Champneys A. Fraser WB. Galan J. Acheson D.
547	Dpiv-driven flow simulation: a new computational paradigm	Ma X. Karniadakis GE. Park H. Gharib M.
567	The high-rate response of an elastomer	Bourne NK. Millett JCF.
577	Dynamics of polar reversals in spherical dynamos	Chossat P. Armbruster D.
597	On vortex waves in compressible fluids. ii - the condensate vortex	Roberts PH.
609	On the existence and uniqueness of the stationary solution to equations of natural convection with boundary data in l-2	da Rocha MS. Rojas-Medar MA. Rojas-Medar MD.
623	Distinguishing population processes by external monitoring	Jakeman E. Hopcraft KI. Matthews JO.
641	Polarization phase relationships via multiple morse wavelets. ii. data analysis	Olhede S. Walden AT.
659	Limit analysis of ductile composites based on homogenization theory	Li HX. Liu YH. Feng XQ. Cen ZZ.
677	Effect of thermo- and diffusiophoretic forces on the motion of flame-generated particles in the neighbourhood of burning droplets in microgravity conditions	Ben-Dor G. Elperin T. Krasovitov B.
705	Shock interaction with solid particles in condensed matter and related momentum transfer	Zhang F. Thibault PA. Link R.

727	On a general kinetic equation for many-particle systems with interaction, fragmentation and coagulation	Belavkin VP. Kolokol'tsov VN.
749	Two-dimensional wavelike equilibrium states in the wall injection-induced planar taylor flow	Griffond J.
773	Magnetoconvection in a rapidly rotating sphere: the weak-field case	Jones CA. Mussa AI. Worland SJ.

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817	Polyphase power-residue sequences	Green DH. Green PR.
829	Curvature effects in vesicle-particle interactions	Rosso R.
853	Existence of solutions to the efros self-consistency equation in all dimensions	Yang YS.
863	Dynamic eshelby tensor and potentials for ellipsoidal inclusions	Michelitsch TM. Gao HJ. Levin VM.
891	Granular finger formation in a rotating cylinder	Shen AQ.
911	Central configurations in three dimensions	Battye RA. Gibbons GW. Sutcliffe PM.
945	Nonlinear riemann-hilbert problems with lipschitz-continuous boundary data: doubly connected domains	Efendiev MA. Wendland WL.
957	The measurement of lubricant-film thickness using ultrasound	Dwyer-Joyce RS. Drinkwater BW. Donohoe CJ.
977	Extinction behaviour for two-dimensional inward-solidification problems	McCue SW. King JR. Riley DS.
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1021	On the nonlinear dynamics of wave groups produced by the focusing of surface-water waves	Johannessen TB. Swan C.

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1053	Long-time behaviour of magnetic field in two dimensions	Klapper I.
1063	Phytoplankton biomass and residual nitrate in the pelagic ecosystem	Platt T. Broomhead DS. Sathyendranath S. Edwards AM. Murphy EJ.
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1117	Analytical solution of excitation of lamb waves in plates by inter-digital transducers	Jin J. Quek ST. Wang Q.
1135	On the sink strength and permeability of micro-cracked arrays	Markov KZ.
1153	Numerically inverting a class of singular fourier transforms: theory and application to mountain waves	Inverarity GW.
1171	Signal analysis through analog representation	Nikitin AV. Davidchack RL.
1193	On the decay and drift of free-surface perturbations in viscous thin-film flow exterior to a rotating cylinder	Hinch EJ. Kelmanson MA.
1215	Conserved currents of massless fields of spin s ¿= 1/2	Anco SC. Pohjanpelto J.
1241	Kinematic dynamos driven by thermal-wind flows	Sarson GR.
1261	The optical singularities of birefringent dichroic chiral crystals	Berry MV. Dennis MR.
1293	The orientation of gyrotactic spheroidal micro-organisms in a homogeneous isotropic turbulent flow	Lewis DM.

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1	Generalized-screen approximation and algorithm for the scattering of elastic waves	Le Rousseau JH. de Hoop MV.
35	Uniqueness and reciprocity theorems for linear thermo-electro-magneto-elasticity	Li JY.
45	Vibrations of lattice structures and phononic band gaps	Martinsson PG. Movchan AB.
65	Nutrient uptake by a self-propelled steady squirmer	Magar V. Goto T. Pedley TJ.
93	On the evolution of time-dependent localized disturbances to dean flow in a channel with slowly varying curvature and gap-width	Eagles PM.
105	On helical shear of a compressible elastic circular cylindrical tube	Kirkinis E. Ogden RW.
123	Exact solutions for axially varying three-dimensional twist motion in a neo-hookean solid	Novozhilova L. Pence TJ. Urazhdin S.
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777	Uniform asymptotic expansion of the square-root helmholtz operator and the one-way wave propagator	De Hoop MV. Gautesen AK.
801	Analytical and numerical investigation of the resolvent for plane couette flow	Liefvendahl M. Kreiss G.
818	Congestion on multilane highways	Greenberg JM. Klar A. Rascle M.
834	Acoustic propagation in dispersions and the geometric theory of diffraction	Harlen OG. Holmes MJ. Povey MJW. Sleeman BD.
850	Connecting a discrete ionic simulation to a continuum	Nadler B. Naeh T. Schuss Z.
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889	The bifurcation structure of the holling-tanner model for predator-prey interactions using two-timing	Braza PA.
905	A terrain-following boussinesq system	Nachbin A.
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937	The coupling of motion and conductive heating of a gas by localized energy sources	Sanchez AL. Jimenez-Alvarez JL. Linan A.
962	Generalized taylor-aris dispersion in spatially periodic microfluidic networks. chemical reactions	Dorfman KD. Brenner H.
987	Realizable (average stress, average strain) pairs in a plate with holes	Milton GW. Serkov SK. Movchan AB.
1029	Double hopf bifurcations in the differentially heated rotating annulus	Lewis GM. Nagata W.
1056	Depinning transitions in discrete reaction-diffusion equations	Carpio A. Bonilla LL.
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418	Numerical method for shape optimization using meshfree method	Kim NH. Choi KK. Botkin ME.
430	Perimeter control in the bidirectional evolutionary optimization method	Yang XY. Xie YM. Liu JS. Parks GT. Clarkson PJ.
441	Improving efficiency of evolutionary structural optimization by implementing fixed grid mesh	Kim H. Querin OM. Steven GP. Xie YM.
449	Shape optimization of curves and surfaces considering fairness metrics and elastic stiffness	Ohsaki M. Ogawa T. Tateishi R.
457	Intelligent computer-aided design optimization of heat pumps	Wu C. Carr MA.

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2	Nonlinear dynamic system identification for automotive crash using optimization: a review [review]	Kim CH. Arora JS.
19	Structural optimization using biological variables to help understand how bones design holes	Venkataraman S. Haftka RT. Rapoff AJ.
35	Automated rib location and optimization for plate structures	Lam YC. Santhikumar S.
46	Topology optimization of the primary mirror of a multi-spectral camera	Park KS. Chang SY. Youn SK.
54	Optimal design of a welded i-section frame using four conceptually different optimization algorithms	Jarmai K. Snyman JA. Farkas J. Gondos G.
62	A note on stress-constrained truss topology optimization	Stolpe M. Svanberg K.

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297	Higher-order solitons in the n-wave system	Shchesnovich VS. Yang JK.
333	Flow past a swept wing with a compliant surface: stabilizing the attachment-line boundary layer	Allen L. Bridges TJ.
351	Weakly nonlinear stability analysis of frontal polymerization	Gross LK. Volpert VA.

377	Determinants of random matrices and jack polynomials of rectangular shape	Andrews GE. Goulden IP. Jackson DM.
391	A note on the jump conditions for systems of conservation laws	Srinivasan GK. Sharma VD.

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117	Effect of cooling rate on fracture behavior of polypropylene	Elmajdoubi M. Vu-Khanh T.
127	Crack size and speed interaction characteristics at micro-, meso- and macro-scale	Sih GC. Jones R.
137	Effect of transverse stress on switch-toughening of ferroelectrics	Cui YQ. Yang W.
143	Subsonic interfacial fracture using strain gages in isotropic-orthotropic bimaterial	Ricci V. Shukla A. Chalivendra VB. Lee KH.
163	Strength of damaged polycarbonate after fatigue	Wang B. Lu H. Tan G. Chen W.
169	Crack bifurcation predicted for dynamic anti-plane collinear cracks in piezoelectric materials using a non-local theory	Zhou ZG. Sun YG. Wang B.
181	Damage accumulation stages in polycrystalline duralumin under static fatigue loading	Kaminskii PP. Kibitkin VV. Khon YA.

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91	Thin-walled structures as impact energy absorbers	Abramowicz W.
109	Shear strength of empty and infilled cassettes	Davies JM. Fragos AS.
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149	Stability and ductility of thin high strength g550 steel members and connections	Rogers CA. Yang D. Hancock GJ.
167	Numerical simulation of structural behaviour of transmission towers	Albermani FGA. Kitipornchai S.
179	The finite element method for thin-walled members - basic principles	Bakker MCM. Pekoz T.
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207	Some observations on the post-buckling behaviour of thin plates and thin-walled members	Rhodes J.
227	Finite element limit load analysis of thin-walled structures by ansys (implicit), ls-dyna (explicit) and in combination	Rust W. Schweizerhof K.
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271	Sensitivity analysis of thin-walled members, problems and applications	Szymczak C.

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317	Critical sizes of ground and underground horizontal cylindrical tanks	Magnucki K. Stasiewicz P.
329	A concise introduction to the idealized structural unit method for nonlinear analysis of large plated structures and its application	Paik JK. Thayamballi AK.
357	On some aspects of the modified tsai-wu criterion in thin-walled composite structures	Kolakowski Z.
375	Pseudo-linearization procedure of nonlinear ordinary differential equations for large deflection problem of circular plates	Chen YZ. Lee KY.

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293	Dirichlet-to-neumann map for three-dimensional elastic waves	Gachter GK. Grote MJ.

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333	Acoustical validation of the rheological models for a structural bond	Vlasie V. Rousseau M.
351	Damping of large-amplitude solitary waves	Grimshaw R. Pelinovsky E. Talipova T.
365	A level set-based eulerian approach for anisotropic wave propagation	Qian JL. Cheng LT. Osher S.
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11	Propagation of sh elastic waves in deep sedimentary basins with an oblique velocity gradient	Luzon F. Ramirez L. Sanchez-Sesma FJ. Posadas A.
25	A dispersive effective equation for wave propagation through spatio-temporal laminates	Weekes SL.
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53	On helicoidal rectangular coordinates for the acoustics of bent and twisted tubes	Campos LMRC. Serrao PGTA.
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93	Modelling nonlinear dynamics of shape-memory-alloys with approximate models of coupled thermoelasticity	Melnik RVN. Roberts AJ.
105	Splitting of energy of dispersive waves in a star-shaped network	Ali Mehmeti F. Regnier V.
119	Flatness-based control of a timoshenko beam [german]	Rudolph J. Woittennek F.
129	On the scattering of point-generated electromagnetic waves by a perfectly conducting sphere, and related near-field inverse problems	Athanasiadis C. Martin PA. Stratis IG.
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249	Mixed finite element methods with discontinuous pressures for the axisymmetric stokes problem	Ruas V.
265	Response of a diffusion-wave system subjected to deterministic and stochastic fields	Agrawal OP.
275	The courant-herrmann conjecture	Gladwell GML. Zhu HM.
282	On bilateral convergence of halley's method	Podlevskyi BM.
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112	An analytical solution of the s-model kinetic equations	Valougeorgis D.
125	External stokes flows in non-regular domains and generalized kutta-joukowski condition [french]	Razafimahery F.
149	Analysis of 2d piezoelectric strips and semi-strips	Hu YT. Yang JA. Jiang Q.
160	Incremental behaviour of hyperelastic dielectrics and piezoelectric crystals	Baesu E. Fortune D. Soos E.
179	A comment on the series solution of the solitary-wave problem	Engevik L.
184	Stagnation flows with slip: exact solutions of the navier-stokes equations	Wang CY.
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224	Global attractor for damped semilinear elastic beam equations with memory	Marzocchi A. Vuk E.
235	Local first integrals of differential systems and diffeomorphisms	Li WG. Llibre J. Zhang X.
256	On homoclinic bifurcation emanating from takens-bogdanov points in hamiltonian systems	Du WH. Huang MY.
273	The linearized boltzmann equation: concise and accurate solutions to basic flow problems	Siewert CE.
304	Stokes flow for the axisymmetric motion of several spherical particles perpendicular to a plane wall	Elasmi L. Berzig M. Feuillebois F.
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349	Linear and semi-linear reinforcement problems by thin layers	Mabrouk M. Samadi H.