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Executive summary

1. Scope

Solid mechanics is a basic scientific discipline which provides the theoretical foundation, experimental support, solution methodology and computational tools for analysis, design, construction, manufacture, and behavior prediction in service of many devices, machines, materials, structures and large complex systems that are essential to the existence and progress of an advanced civilization. It is concerned with both manmade, natural and living solid objects, and with all aspects of their physical behavior that affect their function, integrity or service life expectancy.

Although an extraordinarily large fraction of work in solid mechanics is directed to engineering, it is also a major discipline of scientists concerned with the solid earth and planets (earthquakes, volcanoes, geomorphology, plate motion, mantle flow, impact cratering, etc.) and there is a substantial effort in biology and medicine (physiology, orthopedics) which is basically solid (and fluid) mechanics. Further, in the last 10 or so years, there has been a major trend among condensed matter and statistical physicists to work in that area, principally on crack dynamics, tribology, granular flow, and crumpling of thin sheets or membranes.

The contents of this volume offer examples of some of the activities that are currently at the forefront of solid mechanics research, and also illustrate the vast reach of the discipline and of its interactions with other science and engineering endeavors.

2. Drivers

Since the dawn of civilization, evolving human understanding of what are now areas of solid mechanics has played an enabling role in the manufacture of stone, wooden and metallic tools, weapons and armor, in erection of buildings and fortifications, and of such impressive structures as the pyramids, obelisks, temples, cathedrals and castles. However, its modern development was inspired by the Industrial Revolution, and in the last fifty years propelled by the demands of defense, power generation, transportation and space exploration, and by the present and future requirements of many technologies and conservation efforts.

The field that has grown from these roots now integrates the wealth of knowledge accumulated in the past to provide solutions to new problems and to address challenges which involve unconventional and sometimes as yet unproven but innovative research ventures. Prior to 1989, military applications, with their demands on high technology and performance and their generous budgets, tended to overwhelm the civilian applications. In the past decade, this barrier separating the two distinct constituencies has all but disappeared. In its place is a broad and forceful dictum, even urgency, to consider cost effectiveness

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as well as performance. This includes all aspects of solid mechanics as seen through micro and macro materials and structures applications. It implies emphasis on research driven innovative and advanced techniques and technologies, and departure from traditional engineering approximations.

Intellectual curiosity, interaction with mathematics, physics, chemistry, materials science, medicine, geology and other related disciplines, useful applications in commercial, military and dual-use technologies, natural calamities and major disasters have been foremost among the driving forces of solid mechanics research.

The intellectual enterprise resulted in the discovery of basic concepts of mechanics, such as uniqueness theorems and extremum principles, balance laws and constitutive theory. It has formed the basis for rigorous mathematical formulations and solution methods for specific problems that are encountered in analysis and design with a variety of materials and structural geometries. Applications to actual problems require formulation and experimental verification of constitutive relations that govern the thermomechanical and often time-dependent behavior of metals, ceramics, polymers and composites, as well as semiconductors, bone and tissue, ice, granular materials, concrete, soils and rock masses, the earth crust, and many other materials. This has generated both the tools and data bases for using these materials in appropriate applications that meet performance, life expectancy and cost criteria. Interactions with materials science have inspired a major effort in micromechanical modeling of material behavior. The results have revealed many connections between microstructures and macroscopic properties; they also elucidated mechanisms of damage and fracture of many natural and structural materials, and thus opened the way to the development of both improved and new materials, and composite materials in particular.

Applications of solid mechanics research can be found in most products of such engineering disciplines as aeronautical, civil, mechanical, and naval architecture. Other areas which benefit are bioengineering and medicine, chemical engineering, computer science, electrical, electronic and electric power engineering, fluids engineering and materials engineering. They also play a central role in analyses of structural damage and failures caused either by natural causes, such as earthquakes, or by numerous examples of human ignorance, errors, or hostile action, which have led to much better understanding of fracture and fatigue processes, of the role of environmental factors, and to improved design and solution techniques.

3. Elastic material behavior

For materials that deform in proportion to the magnitude of the applied forces and temperature changes, and reverse to their original shape immediately after unloading, the requisite tools are provided by the linear theory of elasticity and thermoelasticity. Most structural materials, such as metals and polymers at ambient and elevated temperatures, and ceramics even at high temperatures deform in this manner. Experimentally observed response of linearly elastic materials and structures typically agrees with theoretical predictions. Since this is the oldest area of solid mechanics, most problems are well understood, especially those involving homogeneous isotropic materials. However, the emergence of fibrous composite materials and laminated structures, which are macroscopically anisotropic, as well as the use of large metallic single crystals in high-temperature applications, has focused attention on the much more complex problems of anisotropic elasticity and thermoelasticity. This is an active research area, reviewed in this volume by Thomas C.T. Ting for quasi-static loading problems and by David M. Barnett for wave propagation problems under dynamic loading. Response to transient thermal loads is discussed by Richard B. Hetnarski and J. Ignaczak.

4. Inelastic materials

Constitutive theories for inelastic materials are broadly divided into inviscid, or time-independent, and viscous, which recognize the effect of time and/or loading rate on material response. A similarly broad and often fuzzy division associates the mathematical and physical theories of plasticity and viscoplasticity with the behavior of metals, and also soils, and the theories of vicoelasticity with the behavior of plastics, rubbers, ice and biological materials.

Material behavior at strains beyond the linearly elastic region is, in general, very complex. Modeling of response to loads and temperature changes is difficult and often has to rely on simplifying assumptions. Agreement between model predictions and experimental observations is often limited to simple loading cases. The constitutive relations obtained from various models typically lead to nonlinear partial differential equations that require numerical solutions. These have been constructed for many material models and can be applied to most geometries, however, their value is diminished by the frequent absence of reliable constitutive relations for complex loading conditions. This area of solid mechanics offers many challenges that need to be faced in an effort to build more efficient devices and structures for service in exacting loading, temperature and corrosive environments.

The overall goal of one class of current efforts aimed at improving the accuracy of inelastic constitutive relations is to construct well-defined, reliable connections between material microstructure and the macroscopic response of structural metals. The material structure is a collection of many features, such as chemical composition, atomic structure of the crystal lattice, precipitates and defects, dislocation structures within individual grains and subgrains, grain size and grain boundary deformations. With few exceptions, these features evolve during deformation and with time. Successful modeling of their role could suggest interventions on the micro-level, which are becoming more feasible through novel fabrication and rapid prototyping techniques, that would generate desirable behavior modifications on the macroscale. Such efforts involve modeling on many different size scales, and while much insight has been gained within the respective scales, connections between scales, especially those close to the opposite ends of the spectrum, remain often elusive.

Problems of this kind fall within the general scope of hierarchical modeling, which attempts to span increasingly large size differences, reaching now all the way to atomic-scale simulations. An outline of some of these efforts and their potential impact in such areas as crystal plasticity, modeling of micromechanical devices, and nanotechnology are outlined in the chapter by E. B. Tadmor, R. Phillips and M. Ortiz. The use of advanced computational techniques in constructing hierarchical models of plastic deformation of metals are described in the chapter by P. Dawson. Novel plastic deformation mechanisms that have been recently identified on the micron scale are reviewed by J. W. Hutchinson.

Demands for constitutive models of a variety of inelastic materials that are used in current structural applications cannot be met by purely hierarchical approaches at this time. Instead, phenomenological models of inelastic deformation of metals and polymers are required for structural analysis and design. New insights that incorporate elements of thermodynamics of state variables, micromechanics and hierarchical multiscale modeling, and utilize accumulated experimental data for many systems under more complex loading and temperature conditions, have enabled recent improvements in this important area. The chapters written by D. L. McDowell and by E. Krempl offer comprehensive reviews of these efforts in metal plasticity and viscoplasticity in ambient and high temperature applications.

The linear time-dependent behavior of polymers and other solids that comply with the Boltzmann superposition principle is described by the linear theory of viscoelasticity that is well understood. Solutions to problems involving the linear theory can be found by standard methods. However, the behavior of many nonmetallic materials, such as plastics, rubber, asphalt concrete, ice, polymers and biological materials is characterized by nonlinear time dependent processes, and is driven by many dissimilar deformation mechanisms that are very different from those observed in metals. Due to the complexity and variability of the microstructures comprising the different materials systems, understanding of material-specific deformation mechanisms is still uneven and incomplete. Nonequilibrium thermodynamics has proved useful in constructing both general and specific mathematical models that describe the time histories of stress and strain, as functions of the history of applied load, temperature, moisture, and other environmental parameters. An overview of research efforts and accomplishments in modeling such nonlinear viscoelastic solids is presented in the chapter by R. A. Schapery.

Response of materials under dynamic loading, at strain rates up to 10/s, is encountered in many situations associated with vibrations, impact, explosions, armor penetration, high speed machining and metal forming, operation of high acceleration devices, and rapid crack propagation. The dynamic mechanical response of nearly all materials is generally different from that at lower loading rates, often generates heat associated with plastic work, and is inherently nonlinear not only in metals, but even in such nominally elastic–brittle substances as glasses and ceramics. When material disintegration or localized structural failure concludes the dynamic loading event, damage evolution becomes a part of the deformation process and contributes to the observed overall strain. A broad outline of these efforts and results for metals, glasses and ceramics is presented in the chapter written by R. J. Clifton.

Implementation of solid mechanics principles and constitutive relations in formulations and solutions of specific problems must be supported by measurements in either laboratory experiments or by structural monitoring in the field. Special skills are required, both in choosing appropriate instrumentation, in selecting the key aspects of particular theoretical results that can be tested, and in organizing what is often a collective effort. Adequate understanding of material or structural behavior cannot be obtained without experiment; indeed such insights are often useful in the development of valid theories. In his chapter, Wolfgang G. Knauss guides the reader through some of the history of the subject, and the successes and challenges of this field.

5. Fracture, fatigue and damage

No area of solid mechanics has been more driven by response to structural failures than fracture mechanics. Early on, there were only sporadic failures in cast iron and steel structures, almost all at cold winter temperatures. These affected storage tanks, gas pipelines, smokestacks and ships, including—as we now know—the Titanic. Those were mostly puzzling to the engineers of the day. As welding became more widely used in steel structural joints, and the metallurgy as well as the residual stresses generated by the process remained unexplored, brittle fracture became more frequent, particularly in cold winter months. Several catastrophic failures of welded railroad bridges in Belgium in the 1930s provided a significant early warning. However, only the widespread damage from brittle fracture that affected some 20% of the 5000 Liberty and Victory ships built in the United States during WWII created sufficient impetus for focused, federally sponsored research of fracture problems. This work was pioneered by the Navy since the late 1940s, and later also conducted by other military and civilian services and many industrial organizations.

In his chapter, Fazil Erdogan leads the reader through some of this history, as well as through the theoretical developments that brought about a fairly good understanding of fracture processes, their causes and prevention. Many of the key results are now widely known in the engineering community, and have been incorporated into ASTM standards, design codes and inspection procedures. Another chapter by Ares J. Rosakis and G. Ravichandran examines progress in the area of dynamic crack propagation, where much work remains to be done. Of course, these efforts have been drawing upon all available knowledge in solid mechanics, from basic principles, constitutive laws at both low and high loading rates, micromechanics of the separation processes, to solution procedures and, as they became available, numerical computations. Given the progress that fracture mechanics technology has achieved in damage and fracture prevention, it would be difficult to overestimate the significance of the contributions that solid mechanics has made, to preservation of both human life and economic resources.

Of course, catastrophic fracture is often preceded by slow extension of fatigue cracks in structures subjected to cyclic load or vibration. Since even very small flaws may initiate such cracks, understanding of the fatigue process and experimental measurement of crack extension rates in specific material systems are of vital importance. A salutary reminder has been provided by the recent failures of jet engine parts of military aircraft that caused numerous crashes in the last few years. The chapter by Robert O. Ritchie gives much insight into the mechanisms of fatigue, together with a wealth of experimental data.

Unhindered extension of a single crack is not necessary for loss of structural integrity or function. Degradation of stiffness and strength can be caused by accumulation of damage, such as local debonds and other defects that form systems of distributed microcracks, constrained from propagating beyond some small subcritical length. Such constrained cracking may come from many sources and in many shapes, especially in composite materials and some polycrystals, with constituents of different strength and toughness, and numerous interfaces. Modeling of the gradual evolution of this irreversible rearrangement of microstructural geometry, of the possibly inelastic deformation of the multiply connected solid, and of the resulting changes in the overall response is the principal challenge of research in damage mechanics, presented here in the chapter by Dusan Krajcinovic.

Inspections are essential for prevention of structural failure. Quantitative nondestructive evaluation (QNDE) that relies heavily on ultrasonic techniques, discussed here in the chapter written by Jan D. Achenbach, provides the means for assessing structural deterioration by measuring material stiffness, and by detecting and characterizing internal flaws. New techniques discussed in this chapter, such as acoustic microscopy and laser-based ultrasonics, actually feature results of solid mechanics wave propagation research and are being used to preserve the function of devices and structures exposed to potential degradation in service. It is pointed out that theoretical and experimental QNDE results should be integrated with failure mechanics-based reliability considerations for life prediction and life extension of periodically inspected structures.

It has been known for many years, even centuries, that nominal strength may decrease with increasing actual physical size of the object. This has been generally attributed to the fact that large material volumes imply greater probability of critical flaws or low strength subvolumes. Of course, fracture mechanics predicts a decrease of strength with increasing crack length, however, many results that demonstrate the effect of size on strength cannot be explained by fracture mechanics, for the rather obvious reason that propagation of a single crack is not the only mechanism of failure. Instead, progressive damage in various distributed or localized forms often determines the failure mode and thus the observed strength. The size effect is then caused by the availability of energy released by the damage events, which increases for the most part with the second power of structural size, and the energy requirements of crack formation, which increase only linearly with size. The complexity and diversity of failure mechanisms in different structural materials has promoted much recent interest in this subject, as discussed in one of the chapters written by Zdenek P. Bazant.

6. Composite and cellular materials

Many demands of both current and future technologies can not be met by conventional materials such as metals, ceramics or plastics. While each have their applications in large segments of many industries, the range of their properties is limited. However, their combinations in composite systems often create materials with certain properties that are far superior to those of the individual constituents. Of course, many examples of composite systems have been created by early civilizations, such as straw-reinforced mud bricks, and laminated archery bows and swords, and well before that by plants and animals, some with properties that appear to merit human imitation, such as abalone shells.

Modern recognition and exploitation of the true technological potential of composite materials and structures started only in the 1950s. Solid mechanics research of the connections between microstructural geometry, constituent properties and macroscopic behavior of these new material systems enabled rational selection of the components and their geometries, and generated design guidelines for both composite materials and structures. This effort, and parallel progress in materials science and fabrication technology, produced an entirely new and still expanding class of materials and structures with a wide and steadily increasing range of properties and applications.

Starting in the late 1960s, the first focus of solid mechanics composites research has been directed at aerospace structures, where the weight, stiffness and strength advantages of these materials are needed most. However, inexpensive fabrication methods for ever larger parts of complex shape have made composites attractive to many other applications. For example, corrosion resistance of certain polymer matrix systems suggests use in ship and other ocean structures, as well as in light commercial and military vehicles, and even bridges and industrial buildings. In contrast to the thin laminates used in aerospace structures, these applications utilize thick laminates and sandwich plates to support both tensile, compressive and impact loads in hostile environments. A different set of requirements on performance and cost, and new research challenges arise in this context. Many problems related to design and analysis, reliable fabrication, joining, maintenance and recycling of these new classes of composite structures remain to be explored.

Fibrous composites, made of aligned, strong and stiff fibers embedded in light polymer, metal or ceramic matrices, and featuring high strength and stiffness together with low weight, and, where needed, dimensional stability, became prominent in spacecraft and both military and civilian aircraft structures. Light metals, such as aluminum and titanium, as well as intermetallics and ceramics reinforced by aligned ceramic fibers or fabrics offer high strength, stiffness, toughness and creep resistance at temperatures which lie beyond the useful reach of many current high-temperature alloys. Commercial use in components of electronic packaging with designed thermal expansion and conductivity, as well as in large structures, such as boats, vehicles and sports equipment, contributed to volume expansion and cost reduction of this technology, and thus to replacement of traditional materials. Hundreds of large and small companies now offer composite material and laminate stock and products, ranging from prosthetic devices and hand tools to beams, pipes, boats and airplanes.

Discontinuous reinforcements, with whiskers, short fibers and particles of various compositions, shapes and sizes is also widely used to increase overall stiffness, strength and/or toughness, or metals, polymers and ceramics. It also serves to modify other effective physical properties, such as electrical and thermal conductivity, thermal expansion, and piezoelectric and magnetic constants. The advent or novel fabrication and rapid prototyping techniques has opened the way to creation of several special composites, such as fibrous monolithic ceramics consisting of densely packed silicon carbide, silicon nitride or boron nitride crystals in glass matrices. These are being used in net-shaped manufacture of complex parts for high-temperature environments.

Micromechanics, an entirely new area of solid mechanics, has grown from few roots planted early in the century, into a central and even dominant area of solid mechanics. Drawing upon the fundamental principles of continuum mechanics, constitutive relations for the various physical responses of the constituent materials, fracture mechanics, solutions of inclusion problems in elastic and inelastic systems, and novel hierarchical homogenization techniques, micromechanics has created much fundamental understanding of composite material behavior and properties, their design and control. Similar micromechanical insights have also been generated in polycrystaline metals, ceramics and polymers.

Some of these advances are described in the chapters written by George J. Dvorak, Dusan Krajcinovic, Ares Rosakis, Dick Schapery and Salvatore Torquato.

Micromechanical modeling has also supported the development of a very large class of porous and cellular materials of low or extremely low density but reasonable and even considerable mechanical integrity, which are used in numerous products, ranging from energy absorbers in crash protection devices to sporting goods and packaging. They also include honeycomb and other low density cores of sandwich structures and of biological materials such as porous bone and lung tissue. They are used in support of both tensile and/or compressive loads, which often impose different performance and microstructure requirements. While mostly made of polymers, they also appear as porous ceramics and metallic foams. A large variety of these applications and future directions, together with quantitative evaluations of elastic moduli of many two- and three-dimensional geometries of maximum porosity are discussed in the chapter by Richard Christensen.

7. Electronic and active materials

Materials used in electronic devices are usually selected and fabricated with regard to their primary role, which is the control of electric charge. Semiconductors are used most effectively if they are deposited as single crystal thin films on relatively thick substrates. They are not designed to carry mechanical loads, however, they are exposed to significant deformation and related stress fields caused by constrained epitaxial growth, by difference in thermal expansion of the substrate, oxidation, phase transformations, and by assorted intrinsic stresses. This can cause numerous consequences which affect primary function of the semiconducting films. The new developments in solid mechanics research that are essential in maintaining the function of semiconductor films are surveyed by L. B. Freund.

Another objective of this line of inquiry is to assure the physical integrity and function of very small structures subjected to both mechanical loads or constraints and flow of electrons or photons. These structures are found not only in thin films, but also in parts of microprocessors and other electronic devices, and in MicroElectric-Mechanical Systems or MEMS. In contrast to larger objects, small structures experience evolution or configuration changes caused by thermodynamic forces defined by changes in free energy caused by atomic motion. These problems, together with self-assembly of nanostructures, long-range forces and simulation tools are discussed in the chapter written by Zhigang Suo.

Micromechanical material modeling and close contacts with materials science have inspired several new research directions into shape memory, magnetostrictive, ferroelectric and other active materials, as well as into materials and structures which have at least one extremely small dimension, at the micron scale, nanoscale, and lattice and atomic resolution level. One objective of these efforts is to develop connections between fundamental material constants, composition and texture, and where possible, synthesis procedures for materials designed for specific function. For example, active materials are used in actuators and sensors for vibration and motion control of structures, in data storage and processing devices, and in medical applications such as stents that open narrowed arteries. The objectives and accomplishments in the field of active materials are described in the chapter written by Richard D. James.

8. Solids in contact

In a vast majority of cases, transfer of loads between solid objects themselves, and their foundations is accomplished by contact pressure and/or friction. The surfaces in contact may be either stationary or in relative motion, as in sliding, rolling, spinning or indentation. Depending on the particular geometry and history of the load transfer, large local forces and accelerations can be imparted over relatively small areas, resulting in local stress concentrations and, in the case of relative motion, possibly high deformations and deformation rates. Cyclic inelastic deformation surrounding the contact areas may create a residual stress state that restores elastic response in a shakedown state, or it may proceed to accumulate and cause ratchetting and wear. In his chapter, James R. Barber leads the reader through some of the long and rich history of this subject and through the numerous recent developments in the mathematical solutions of contact problems.

Tribology is concerned with problems involving interacting surfaces in relative motion. It investigates the mechanisms and mechanics and the conditions of proper function of many mechanical systems consisting of either joined or proximate moving parts, such as rolling element and fluid film bearings, cams, gears, human joints, magnetic storage devices, pistons, seals, tires and wheels. Since both lubricants and the solid surfaces in contact are under investigation, this area is at the juncture between solid and fluid mechanics. Its economic impact is enormous, in terms of breakdown prevention and life extension of machines and other devices. In their chapter, John A. Tichy and Donna M. Meyer outline some of the history of the subject, and present several interesting examples of application in the technology of hard drives, coatings, gears and cams, seals, biomechanics and MEMS. They also discuss research problems in such areas as rough surface contacts, pitting, and fretting fatigue, with applications in both new and traditional technologies.

9. Geomechanics and ice mechanics

The study of geologic materials and related problems has been one of the central themes in solid mechanics since its inception, when stone was a principal building material, and soil properties had to be considered in foundation design. It retains its important position in solid mechanics because of the numerous applications that rely on the research results. Both geological materials and ice are strongly heterogeneous and often anisotropic; they may contain discontinuities of different sizes, and come in many different forms, with varied properties that are largely unaffected by human intervention. Also, both exist and function on an enormous range of length and time scales. At the low end of microstructural features, mineral components, grain size and porosity, the length scales are similar to those of other engineering materials. However, both natural and man made geologic structures, from faults in the earth crust, to hydrocarbon reservoirs, polar ice packs, mines, tunnels and nuclear waste depositories, to name a few, extend for tens or thousands of kilometers. The time scales are also disparate. They are similar to those of other engineering materials at the shorter scales of fracture and wave propagation in earthquakes or ice breaking, longer in the yearly ice formation and melting cycles, or seasonal storage of natural gas, and involve very long time periods of hundreds or more years between major earthquakes, or the 10,000 years of inaccessible storage requirements imposed on nuclear waste.

As in other solid mechanics problems, the study of geological materials and ice includes theoretical modeling of constitutive behavior with experimental verification. However, these models must often reflect coupling of the mechanical response with chemical interactions with the environment, with internal or external fluid flow, and with thermal effects. This opens special areas of solid mechanics, such as poroelasticity with applications in the petroleum industry and in studies of crustal deformation, or mechanics of hydraulically driven rock fracture that may be accompanied by chemical deposition or dissolution in mining operations or geothermal energy recovery. In a different context, such fractures may result from wave–ice interaction and cause sea ice breakup. Contact problems, particularly those involving frictional slip at high rates and low or elevated temperatures are also of major importance in applications involving both the earth crust movement and ice forces on structures and ships, ridge formation and ice gouging of underwater pipelines. Very interesting surveys of the practical and research problems in geomechanics and in ice mechanics appear in the chapters written, respectively, by John W. Rudnicki and John P. Dempsey.

10. Structures

Among the earliest subjects of solid mechanics research, both analysis and design of most civil, offshore, naval, aeronautical and other structures is relatively well understood. However, major progress has been made only in the last few decades, and has benefited from advances in other areas of solid mechanics, such as plasticity theory, fracture mechanics, computational mechanics, and reliability and life cycle simulations. However, major unresolved issues of fundamental nature remain, both in theory and practice. Some of these translate into or are brought to light by the infrequent structural failures that still occur every few years, sometimes under adverse weather conditions that impose higher than designed loads, or as a result of damage or structural and material deterioration. Others arise with the introduction of new materials, such as composites or high-strength concretes, which have some superior properties as well as weaknesses that have to be respected in design.

These different aspects of structural behavior and associated research problems are summarized in three chapters in this volume. The important area of structural stability, for elastic and inelastic systems under both static and dynamic loading is reviewed by Zdenek P. Bazant. The main results in stability of columns frames, arches, as well as thin-walled beams, plates and shells are reviewed. Dynamic instabilities caused, for example, by wind or water loads, by chaotic motion or by localization of damage, or by fracture propagation or large plastic straining are also discussed. It is pointed out that considerable progress has recently been achieved in stability and bifurcation problems of damage localization and fracture, and in the thermodynamic analysis of stability of state response path, which cicumvents the necessity of dealing explicitly with imperfections.

Mircea Grigoriu surveys the general area of stochastic mechanics that is concerned with response of structural and other systems to loads that are not predictable in some deterministic fashion, and also with materials and structures which have uncertain properties and are exposed to randomly fluctuating loads or other inputs. He introduces the reader to concepts of the probability theory, and to its applications in solid mechanics, in random vibration, and in material design and response.

Plasticity, limit analysis and structural design are the themes of the chapter written for this volume by W. F. Chen. He summarizes the major advances of structural engineering in the last forty years that can be attributed to solid mechanics in general, and plasticity in particular. A brief historical sketch of developments in elasticity, plasticity and limit analysis is presented together with the history of applications of the finite element method, that was originally conceived for solution of civil engineering structural problems. The major topics of the chapter feature design of steel and concrete structures with advanced analysis, and finite block analysis of tension-weak materials.

11. Future research challenges

1. Although the search for quantitative connections between constitutive description of the behavior of inelastic materials and the physical mechanisms which account for that behavior has been underway for some time, unambiguous unifying concepts have been elusive. The increased resolution of

observations afforded by advances in experimental methods and the development of computational strategies which incorporate the most fundamental physics of material characteristics offer the prospect of significant progress in the decades ahead. Understanding of the behavior of inelastic metals, polymers and biological tissues at this level would be a boon to design analysis and simulation studies of a wide range of engineering systems.

2. The characterization of the fracture behavior of nominally homogeneous materials, and the practical implementation of the consequences, is one of the major engineering achievements of the 20th century. While the same basic concepts can be applied on a local scale to each constituent of an inhomogeneous material, such as a composite material or a cellular material, a reliable methodology for predicting failure in terms of the material properties and geometrical configuration of the constituents is not available. Such a methodology is important to full exploitation of these strong and lightweight materials in design and for reliable lifetime assessment through nondestructive monitoring.
3. Affordability requirements have promoted exploration of low cost, high quality composites, compared to the high cost systems for aerospace applications, and resulted in development of new processing techniques, such as resin transfer molding. Both the mechanical behaviour and failure modes of these new, usually fabric reinforced systems are different from those of the aligned fiber systems extensively studied in the past. Modelling and experimental investigation of deformation, damage and failure processes, and their temporal and spatial resolution, confirmed by nondestructive and other evaluation techniques are needed for development of rational life prediction methods. Formulation and experimental validation of constitutive relations, fracture and failure criteria, scaling laws, and understanding the role of environmental conditions such as moisture, sea water and temperature extremes, and of their coupling with complex stress fields present a new set of challenges to solid mechanics research in this field.
4. The development of material systems for nonstructural applications normally proceeds without concern for mechanical properties or strength, as has been the case with microelectric devices, sensors, optical fibers and microsurgical devices, for example. As the technology is refined to meet expectations on performance and reliability, mechanical failures or other impediments to proper function arise during fabrication or service due to mechanical effects. Solid mechanics research is already providing direction for advancing these commercially significant technologies. Important phenomena commonly involve the interaction between mechanical fields and electrical, magnetic, chemical or optical effects, and the complete understanding of such coupled phenomena poses a challenge for the field in the years ahead. Potential applications of MicroElectro-Mechanical Systems (MEMS) for aerodynamic sensors and actuators, microgyroscopes, surgical instruments and the general miniaturization which is necessary for integration of such devices onto silicon chips represent particular challenges for the field.
5. Research in solid-state physics has provided robust representations of the interactions between atoms of crystals and between molecules of polymers, for example. These interactions ultimately dictate the overall behavior of small material structures. Efforts to establish connections between boundary data and mechanical response of real systems, which are the features that can be controlled or observed in experiments, have been impeded by the complexity of actually accounting for the behavior of the roughly one hundred billion atoms in a crystal with a volume of one cubic micron, for example, over an observable time range. The goal is not hopeless, however, because most of the detailed information in the model is nonessential for understanding behavior determined by the making and breaking of a relatively small number of chemical bonds. Modeling strategies are required which focus on only the essential features in an adaptive way controlled by the system behavior itself rather than by some arbitrary a priori prescription.

This modeling strategy, which is needed to accommodate the widely varying length scales between interatomic and bulk behaviors of crystals or between single fiber and structural behavior of composites, is essential for the reliable exploitation of emerging material fabrication techniques.

6. For the science of earthquakes, there is the need to understand the dynamics of rupture propagation on faults and radiation of ground motion, and to understand factors controlling the population of earthquakes on fault systems; for granular materials, to understand processes of flow and failure, with applications in materials handling, storage, and transport, in foundation engineering, in natural mass-wasting in landslides, and in liquefaction during earthquake shaking. In volcanology, to understand the way magma ascent processes hydraulically crack the crust, create and inflate storage chambers within the hot rock that induce local seismic failures, and lead to eruptions of different styles. In tsunami generation, to understand what processes control the propagation of earthquake rupture into the shallow thrust interface at subduction zones (hence coupling to tsunami generation) and induce undersea landslides, also a tsunami source.
7. As generally recognised, inadequate durability is a major problem civil engineering infrastructure, causing enormous losses to the national economy. The theoretical aspects of durability of concrete structures are being addressed in a fundamental and consistent manner by the recently initiated efforts in chemo-plasticity and chemo-mechanics. Such efforts, coupled with advances in pore vapor pressure analysis, have already improved understanding of damage processes, and of the often explosive spalling of concrete subjected to fire, as experienced in the Channel and Mont Blanc Tunnel fires. This is particularly severe problem, for example, in design of radioactive waste storage. Applying solid mechanics approaches to new or improved civil engineering materials and relating materials science aspects to design are among the major challenges in this field.
8. In the area of quantitative non-destructive evaluation of structures, theoretical and experimental QNDE results should be integrated with failure mechanics based reliability considerations, for life prediction and life extension of structures, in the context of life cycle engineering. Using measurement models, simulations of the probability of detection should be pursued to facilitate this effort. For the evaluation of material properties and for intelligent processing methods, work is needed on the development of new sensors and related techniques based on laser ultrasonics.
9. A particularly vital aspect of the solid mechanics research enterprise is the population of young graduate students and post-doctoral scholars who are being prepared for productive careers as researchers or as engineers charged with implementation of research results. It is essential for the continued health of the discipline that proper balance be sought between a focus on the fundamental tenets of the field and the immediate needs of designers and developers. The disciplinary structure of the field, which is the feature that provides the long-term flexibility and diversity of researchers, should be implanted and continuously reinforced throughout an education. On the other hand, the field is but an element in a complex and evolving society. It is equally important that young people gain an understanding of where their discipline fits into this structure, and where the current needs and opportunities for solid mechanics research lie. Due to the transitory nature of the latter structure, the contemporary needs and opportunities serve as instructive examples of the way fundamental research relates to technological opportunities. The task of providing a balance between the disciplinary foundations and representative examples of contemporary practice is a continuous challenge.

George J. Dvorak with members of the Advisory Board