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Guest Editorial

Vision of the Future of Solid Mechanics

Although mechanics is the oldest field of science, it is still advancing rapidly, driven, in all areas of technology, by the need:

(1) to develop fundamental understanding of material and system behavior at *multiple scales*;
(2) to deduce realistic *mesoscopic and macroscopic models*, and verify and calibrate them experimentally;
(3) to advance the understanding of *failure mechanisms* of materials, structures, and systems;
(4) to achieve *mechanically and functionally superior* performance, ensuring a near-zero incidence of failure and minimal long-term deterioration; and
(5) to advance the understanding and *robustness* of diverse *complex* systems such as those found in biology and nanotechnology.

Advances in solid mechanics are made possible by new superior instrumentation, novel and ingenious experimental methods, better mathematical models, ever more powerful computational tools, and new and growing interactions with an ever expanding range of disciplines.

Importance of Mechanics in the Modern World

The successful development of technology in broad fields of activity still crucially depends on advances in solid mechanics and its application. Opportunities can be identified in areas such as electronics, where devices depend on successful utilization of mechanical effects as much as on electrical phenomena, with examples including epitaxy, strain dependent band-gaps and the integrity of electrical leads and connections, dies, and circuit boards. Biology, whether related to medical treatments, involving prostheses, stents, and implants, or regarding the growth, function, adhesion, and motion of cells, the conformation and interaction of proteins, and the ubiquity of DNA and other molecules, is replete with issues such as dynamics, compatibility, and constitutive response that are the bread and butter of solid mechanics. Diverse fields of engineering are still vitalized by advances in solid mechanics, including blast resistant structures, tough, strong, and durable advanced materials, thermal protection systems, and deployable structures.

Frustrations exist that can be remedied by future developments in solid mechanics, whether it is the absence of hypersonic vehicles due to inadequacies in stiffness, strength, and temperature resistance of materials, of the unpredictability of earthquakes, landslides, and avalanches due to inadequate advances in the understanding of large-scale frictional cohesive shear fracture in heterogeneous materials. Also, the insufficient durability of hip replacements and other prostheses requires a much better understanding of long-term progressive damage and frictional wear of composites and micro-porous metals. The poor fatigue resistance and durability of systems in aggressive environments demands better technology to avoid many catastrophic failures and to achieve enormous savings by extension of the lifespan of our nation's infrastructure.

Avoidable failures continue to occur, and ensuring that they are not repeated in the future depends on continued advances in solid mechanics. Consider some examples: both space shuttle disasters have been traced to material failure (leakage of a seal in one case and loss of integrity of structure and thermal protection in the other); the crash of a DC-10 in takeoff from O'Hare Airport in 1979 was caused by a fatigue crack in an engine pylon; the crash of an Airbus shortly after takeoff from JFK Airport in 2001 was probably caused by overload fracture in a large vertical stabilizer made of advanced composites; the World Trade Center collapse was triggered by viscoplastic deformation of columns heated by fire; and the giant Sleipner oil platform would not have sunk, and earthquakes would not have destroyed the viaducts in Kobe, Oakland, or Los Angeles, were quasi-brittle compression-shear fracture and its scaling understood.

Evidently, mechanics of solids is the controlling factor in many advanced technologies, a roadblock to implementing innovative technologies, and the explanation for many catastrophes. Advanced experimental methods and large-scale computer simulations are now rendering realistic simulation and prediction feasible. We have great opportunities for research.

We also face challenges in education. We need to attract and train new generations of solid mechanicians at a time when the preparation of the young in mathematics and science is degrading, while many students perceive other opportunities to be more attractive or glamorous, and most universities are no longer interested in mechanics programs. In the face of this, the tensorial nature of solid mechanics, the nonlinearities of constitutive behavior, and the complexities of damage and scaling necessitate prolonged training in a focused program.

Solid mechanics is a unifying discipline. Cutting across many professions, it is perhaps the most interdisciplinary scientific activity in the leading engineering schools. The scientific field is one, but its interventions span mechanical, aeronautical, aerospace, civil, materials, biomedical, chemical, environmental, nuclear, offshore, naval, arctic, and electrical engineering, as well as the sciences of materials, biology, chemistry, physics, geophysics, and planetology.

Challenges and Opportunities for Research

With no claim for completeness, a diverse set can be assembled:

(1) *Multiscale modeling*, connecting the hierarchy of scales in materials (nano-micro-meso-macro), is a dominant trend. Embedding a discrete model at one scale (e.g., atomistic simulation, simulation of discrete dislocations, simulation of particles or fibers in a matrix, the role of nanopores in concrete) into a continuum model at the next higher scale is a challenge where success can yield superior understanding of composites, polycrystals, and porous or cellular materials.
(2) *Failure scaling and size effects* represent a companion problem—that of finding the laws of transition among re-

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gimes whose scaling individually can be characterized by power laws; e.g., the transition from a discrete local scale of fibers or particles embedded in a matrix to a continuum representing a composite; from crystal grains with dislocations to a continuous thin film; from intact rock blocks to a mountain mass intersected by rock joints; or from mile-size ice floes separated by thin ice to the continuous cover of the entire Arctic Ocean.

(3) While *composite materials* had their dawn much before nanotechnology, they still present great opportunities. Their promise for load-bearing aerospace and ship structures resides in their high strength-weight ratio and energy absorption, as well as potentially easier maintenance. Hurdles to overcome exist in processing, fracture and size effect prediction, moisture ingress, and damage detection.

(4) *Nanotechnology* has become a booming field. Design against fracture and debonding of submicrometer metallic *thin films* for electronic components, development of superstiff super-strong *nanocomposites* of low brittleness and wear, exploitation of the symbiotic strength, electronic and thermal properties of carbon *nanotubes*, etc., present unique opportunities for *nanomechanics*.

(5) *Detection of damage* such as cracks and corrosion in aging aircraft, steel bridges, nuclear reactor vessels, ocean structures, etc., is of paramount importance. *Nondestructive* testing requires sophisticated inverse analysis of acoustic wave propagation problems. Despite great advances, much more is needed, not least for fiber and particulate composites where acoustic wave dispersion by inhomogeneities poses hard obstacles to detection.

(6) A related task is the development of sensors, especially *nanosensors*, for "smart" structures and devices that can signal information on their damage, and thus allow automatic structural health monitoring if structural system identification by inverse structural analysis is mastered. *Adaptive smart structures* and devices, capable of controlled expansion, contraction, flexing, and stiffening, will be important for self-deployable space structures, damping of seismic oscillations, etc.

(7) *Chemomechanics*, applied, e.g., to concrete subjected to chemical attack involving diffusion and thermal effects, is a fertile field bound to improve structural durability and serve environmental objectives (e.g., embedding waste glass in concrete). Similar phenomena, such as crystallographic phase conversion, are making polycrystalline *shape-memory* alloys attractive for smart structures. In biology, chemomechanics presents fascinating challenges demanding new multidisciplinary approaches.

(8) *Bio-inspired materials* offer intriguing examples of *mechanical superiority*. The abalone shell achieves its amazing strength, fatigue resistance, and shock resistance by an intricate design and self-assembly of nanoparticles of brittle calcite bound with a small amount of protein-based polymer. Some sponges achieve toughness and robustness by integrating brittle materials over at least seven scales. The combination of strength and deformability of spider thread has not yet been equaled. Such feats demonstrate what is achievable. *Biomechanics*, a long-burgeoning field, appears headed for perpetual growth, with applications to osteoporosis and fracture of bones, large strain of anisotropic blood vessels or soft tissues, etc. This field is today reaching into intriguing questions regarding the cytoskeletons of cells, the conformity and compatibility of biological polymers and proteins, and the mechanical behavior of DNA and related molecules.

(9) *Probabilistic mechanics* and *reliability analysis* have reached a high degree of mathematical sophistication, yet still present great opportunities, especially for extensions of primitive material models to quasi-brittle fracture with localization and scale effects, multiscale and nano-based models, coupling with poromechanics, heterogeneities, diffusion, etc. Advances will especially be required in the understanding of extreme-value statistics of random fields in the context of damage localization, quasi-brittle fracture with size effects, and multiscale models. Because of the large values of empirical safety factors used in mechanical design, rationalizing them with extreme-value based statistical mechanics is an enormously promising prospect.

A host of other challenges could be elaborated on. For all of them, simplicity of modeling will be essential for conquering complexity. Usually, only a few characteristics among many dominate the response of a complex mechanical system. The goal of theory is to identify them and condense them into rationally derived but simple laws describing, at least approximately, the overall behavior of the system. This is what much of materials science has been concerned with.

While simple laws governing the mechanical response of structures will obviously be essential for progress in civil engineering (where thousands of structures, each different, are designed annually), they will be no less important as an optimizing tool in all fields of application of mechanics, including those where only a few new designs appear annually (as in aircraft or automotive engineering). A computer allows a brute-force conquest of complex individual situations, but it is the discovery of a simple mathematical law that lends us general understanding, and thus control.

Progress in developing solid mechanics theories and practical approaches to all these problems is sure to happen eventually, but the question is when and where. An institution, firm, or country that will lead in this pursuit in an aggressive manner will reap many benefits.

Zdeněk P. Bažant