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THE MATERIALS-MECHANICS LINKAGE IN THE ENGINEERING CURRICULUM

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ABSTRACT

Materials Science and Applied Mechanics have become linked strongly in the research and industrial communities, but this trend has not been mirrored in the engineering curriculum in many universities. Materials Science and Applied Mechanics are often taught by different departments, each with different focus and language; rarely is the student provided direct connection between these intrinsically related subjects. This paper presents an overview of the curricular difficulties inherent in this situation, and a number of innovations by which an improved linkage could be obtained. One example to be presented in some detail will be a textbook for introductory Mechanics of Materials, recently prepared at MIT and used in the core curriculum of the Department of Materials Science and Engineering, that emphasizes the materials aspects inherent in the subject.

Keywords: *Engineering, curriculum, materials, mechanics*

INTRODUCTION

Applied mechanics and materials science are broad fields of human endeavor with long histories. Each independently can claim myriad success in technological achievement. *Mechanics* deals with the theoretical and experimental analysis of forces on material bodies, and the resultant motions and deformation that ensue. *Materials Science* is concerned with the atomistic and microscopic structure of material, and the properties resulting therefrom. A working, albeit over-simplified, definition can be taken to be "mechanics is physics, materials science is chemistry."

Unfortunately, many engineering curricula treat these disciplines as wholly independent, usually taught by faculty from different colleges. For example, undergraduate "mechanics of materials" subjects are often taught separately and distinctly form "properties of materials" subjects; a young engineer may never see the connection between the elastic modulus parameter in the beam-bending equation, and the inter-atomic forces which give rise to a material's "stiffness". As another example, applied mechanicians and materials scientists will teach the subject of fracture from widely different perspectives, the former being concerned with mathematical modeling of the phenomenology, while the latter takes an atomistic view of fracture mechanisms.

An Historical Perspective

It is instructive to ask whether historical linkages existed between applied mechanics and materials science. Have these disciplines always been as disparate as they now seem, or did bifurcations occur in a unified past? One approach to answering this question is to review historical writings on a subject that *should* include both disciplines, namely the fundamental subject of “mechanics of materials”.

The early “royal philosophers” like Da Vinci, Galileo, Hooke, Young, and others, were truly “renaissance” scholars, in that they brought with them to their investigations a broad background in chemistry, physics, and mechanics. The development of analytical mathematics and mechanics in the 18th century increasingly fostered specialists, as contrasted with these earlier generalists. At the same time, chemistry and physics were developing as well, and with the expanded use of metals in the industrial 19th century, each began to focus into specialized areas (metallurgy, for example). As specialized bodies of knowledge developed, it became increasingly difficult to be inclusive and bridge across various disciplines.

This divergence continues into modern times. Consider, for example, Seely’s text *Resistance of Materials*[1], which contained a 55-page chapter on “Mechanical Properties of Structural Materials” when it first appeared in 1925. By the printing of the 4th edition in 1955, nearly all mention of material properties has disappeared, save for a discussion on fatigue. One can find today very few Mechanics of Materials texts that combine mechanics and materials science in an integrated and cogent manner.

Need for Integration

Today, examples abound which show the need for engineers and scientists who have an integrated, interdisciplinary background bridging mechanics and materials science. Consider, for example, the important and active area of high-performance composite materials. Here, an intimate knowledge of structure-property relations is demanded for technological advancement. Bulk response can be predicted in an averaged sense using a mechanics approach, which is necessary to design a real composite structure; but only knowledge of the fine-scale (micro- to nano-scale) structure-property relations and interactions among the constituents can lead to an optimal “engineering” of these materials for an intended application.

Another example of the interdependence of mechanics and materials science is the proposed High Speed Civil Transport (HSCT) vehicle. Development of lightweight materials that can operate successfully in very high temperature regimes. A unified effort that understands the thermo-structural environment, together with the possibilities for engineering materials that meet this challenge, will be essential.

Introductory Mechanics of Materials subjects have become highly standardized around the model pioneered by S. Timoshenko[2], which emphasizes direct solutions of simple structures (pressure vessels, trusses, torsion rods, beams, etc.). While this approach has certainly stood the test of time, the present authors feel it has become obsolete, failing to deal with advanced materials encountered frequently in engineering practice, and failing to establish proper links with subjects in the students’ science core curriculum. As a result, Mechanics of Materials tends to become an academic promontory, with many students failing to see how it fits into their overall science and engineering education.

STEPS TOWARD LINKAGE

This paper will argue that a mechanics treatment built around materials concepts provides a much more satisfactory approach. Admittedly, this will be viewed skeptically by some instructors: partly because the Timoshenko approach has become very comfortable and is supported by many high-quality texts, and partly because some engineering faculty have lost familiarity with the chemical aspects of mechanical response. The present authors hope that the advantages inherent in the materials - mechanics linkage can gradually be seen as outweighing these drawbacks.

As elaborated in an extensive review conducted by the National Research Council[3], materials science and engineering is a study of theoretical and experimental relations among:

- A material's *processing*, to include its chemical synthesis as well as subsequent themomechanical treatment and shaping,
- The materials microstructure, as arising from its processing.
- The material's *properties*, arising from its microstructure, and
- The material's *performance* in an engineered structure or product, as dictated by its properties.

Traditional mechanical design employs principally the last two steps, using handbook material properties in selection and sizing to develop a product. This approach has worked for millennia, hut as the examples outlined above indicate is inefficient when designs employ advanced materials whose processing and resulting properties are themselves an adjustable part of the design process. The designer, we argue, should he sufficiently aware of the full materials approach that the shortcomings inherent in treating materials as black boxes can he eliminated.

One approach, of course, is to require that structural engineering students take a subject in materials science and engineering, and many curricula do. However, such subjects are not usually linked specifically to Mechanics of Materials, leaving the student to see the connection. It is far better, we feel, that the materials concepts should be integrated directly into Mechanics of Materials subjects.

A TEXT APPROACH

A curricular revision such as is being proposed here involves a considerable number of small and large changes, too many to elaborate in this short article. Texts must be written anew from a different point of view, and one illustration is the text prepared by one of us (DKR) for use in the undergraduate curriculum in MIT's Department of Materials Science and Engineering. The content of this text is one possibility for a materials-based mechanics subject, and in outline form it includes:

1. Uniaxial response: Hookean elasticity, entropically-governed rubbery elasticity, linear viscoelasticity, transversely isotropic composite laminae.
2. Simple engineering structures: trusses, pressure vessels (including viscoelastic effects), torsion.
3. Generalization to three dimensions: kinematics, equilibrium, tensor transformations, constitutive equations.
4. Bending: beams, plates, composite laminates.
5. Stress analysis: closed-form (including viscoelastic correspondence principle), experimental (strain gages, photoelasticity, Moire, finite element analysis).
6. Yield and plasticity: Tresca and v. Mises criteria, polymer crazing, rate-process treatments, dislocations, continuum plasticity.
7. Fracture: statistics, atomistics, Griffith energy balance, stress intensity approach, fatigue.

Some salient points of this text, from the view of a materials - mechanics linkage, include:

- The traditional topics in Timoshenko - style coverage, such as beam bending and Mohr's circle, are included. Some older topics, such as multiple means of computing beam deflections, have been omitted, but the essential coverage remains.

- The last two chapters, on yield and fracture, deal with materials-dominated concepts (dislocation motion, crack-tip plasticity, etc.) and are more extensive than found in traditional texts.
- Materials properties such as Young's modulus and Poisson's ratio are explained in terms of atomistic mechanisms; for instance bond stiffness and molecular mobility for these two parameters respectively.
- The material's stiffness is also placed in context with the students' thermodynamics subjects, by noting that an increment of mechanical work $f\,dx$ can be accommodated by either an increase in internal energy dU or a decrease in entropy dS:

$$f\,dx = dU - TdS$$

- The internal energy term arises from the bond stiffness as mentioned above, but consideration of the entropic term allows rubber elasticity to be developed in a natural way as well.
- By noting that the configurational changes underlying entropic elasticity are thermally activated rate processes, it is natural to lead from rubber elasticity to linear viscoelasticity.

While the atomistic and thermodynamic treatments seem unusual at first, they allow a smooth pedagogic flow of topics, and they link naturally with core subjects the student might otherwise wonder why they had to be taken.

This text has been used for several terms at MIT as well as several adoptions elsewhere, and apart from relatively minor editorial corrections appears well suited for its intended goals. It remains to he seen whether the material view it presents can eventually impact the teaching of Mechanics of Materials in the broader engineering community.

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