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Linking Mechanics and Materials in Engineering Design: A new Approach

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ABSTRACT

Educating engineering students should involve an integrated approach. Hence we have developed a new course linking mechanics, materials science, and design. The course titled "Mechanics and Materials in Structural Design" educates students in the total design of structures. One important aspect of this model of teaching is to develop multimedia based virtual lab modules. This paper focuses on one such module, namely, "Tension Test of Metals". This module links the mechanics experiment with the fundamentals of materials science and highlights its usefulness in the context of engineering design of structures. With this approach an apparently simple tension test can help the students to better visualize the linkages between materials response at the macro- and atomic-level, and design. Preliminary assessment of the course suggests that this philosophy of teaching and integrated course on design is valid.

1. Introduction

The principal factors for improvement in the performance and reliability of products are the development of new materials, novel use of existing materials, better understanding of the structure-property relationships, and incorporation of both mechanics and materials science in the design of structures. It is proposed to develop a new course, at the junior level in mechanical engineering, linking materials science, mechanics of materials, and design, based on the above-mentioned factors.

In present engineering practice, structural components are designed by using the mechanical behavior of real engineering materials solely in terms of their elastic response. Very seldom is consideration given to the nature of the material and its actual response to forces as the manifestation of its heterogeneous internal structure. This approach to design and instruction in the classroom, where all materials are considered to be homogeneous, isotropic, and linear elastic continuous media, is no doubt a good way to introduce the subject. However, the implications and consequences of the approximations so introduced are generally lost on the learner, and as a result, these useful tools of limited applicability are accepted as a true reflection of the properties of engineering materials.

Most of our knowledge concerning the mechanical behavior of engineering materials is empirical in nature and is derived from phenomenological observations and experiments. However, the more effective way is to develop a more fundamental approach to understanding the behavior of materials. This approach should be based on the analysis of the underlying unifying principles by which the relevant engineering concepts could be understood and further developed. The unifying principles, by which the apparently complex phenomenological behavior of real materials can be interpreted, are the laws governing the formation of matter from atoms and larger structural elements at different levels of aggregation. Thus the deformational properties of a single crystal are closely related to the principles governing the formation of the particular type of crystal out of atoms, ions, or molecules. Similarly, the deformation of polycrystalline metals or polymers is governed by the laws of formation of such materials from single crystals or large molecules, respectively.

The development of new materials, as well as the variation in service conditions of machines and structures, has created many problems that can only be solved by considering the internal structure of the materials, and its response to the applied forces and constraints. For example, the assumptions of homogeneity, isotropy, and time-independent elasticity are irreconcilable with the phenomena of fatigue and creep of real materials. An analysis of the mechanical behavior of such materials requires the consideration of their structure and their phenomenological response interpreted in terms of microstructural changes under the applied loads and conditions. Thus the large-scale behavior can be at least qualitatively predicted from knowledge of the internal structure.

The philosophy and methodology of a new course that will assimilate atomic, micro-structural, and phenomenological materials considerations, and link them with mechanics principles, while teaching a broad and integrated course on total structural design, is presented elsewhere[1-3]. The new course will attempt to integrate the disciplines of applied mechanics, materials science, and design, and enhance the education of undergraduate engineering students. This paper presents an important part of this larger effort; namely, multimedia based development of laboratory modules. In this paper we have discussed the “Tension Test” module for isotropic metallic materials, and describe the deformation response on the basis of atomic- and macro-level mechanisms.

The tension test is one the most important and fundamental tests for determining material properties. Thus a multi-media based lab module for metals has been developed in the Authorware software environment (Macromedia Inc.). This lab-course module links the mechanics experiment with the fundamentals of materials science, and its usefulness in generating design information.

The virtual lab module includes:

- a multimedia presentation of a tensile testing machine

- a multimedia presentation of the different types of tensile test specimens
- the stress-strain diagram for a ductile metal
- a discussion of the data that can be acquired from a tension test
- discussion on the evaluation of material properties from the tensile test data
- detailed reviews of the link between atomic structure and materials deformation under the action of external loading. The reviews include topics such as introduction to link between atomic structure and materials behavior, atomic bonding, crystal structure, atomic basis for elastic and plastic deformation, and fracture in materials
- drill questions and exercises

It is believed that this approach will considerably enhance the understanding of material behavior under different loading conditions, and pave the way for advances in safer and optimum design of machines and structures.

2. Mechanics And Science Of Material Response: Multimedia Enhanced Courseware

The goal is to use modern evolving multimedia techniques to establish, in a variety of representative modern engineering materials, a relationship between macroscopic mechanical behavior and the corresponding mechanisms at the micro and/or atomic level. In addition, this courseware will facilitate active student learning, and reduce reliance on traditional lecture methods of knowledge delivery. It is envisaged to use enhanced computer imagery or a multimedia approach to demonstrate the intimate relationships between macroscopic mechanical phenomena and the associated micro-mechanisms.

More specifically we will investigate establishing the above-mentioned relationships for mechanical behaviors such as elastic deformation, plastic deformation, and fracture, etc. in various materials. Candidate monolithic materials are metals, ceramics, and polymers. However, here we will only concentrate on metals.

As an example, consider a ductile metal (say, aluminum) tension specimen as it is loaded through the elastic and plastic region to fracture. Typically, such a tension test is done at the sophomore or early junior level. However, the students are generally exposed only to macro-deformation phenomena such as elastic modulus, yield strength, ultimate tensile strength, fracture stress, modulus of resilience, and ductility. There is generally no correlation established between these parameters and the atomic structure of the material, dislocation movements, slip planes, grain structure, fracture mechanisms, etc. Through an interactive module, containing a real-time, virtual experiment, we intend to bridge this gap.

A schematic flow chart of one such multimedia module, the "Tensile Test", is shown in Figure 1. When a student/user wants to conduct a virtual tensile test experiment, a set of buttons (choices) appear on the screen, e.g., material of the specimen and test speed. When the user clicks on material of the specimen, a library of materials is available for materials selection. The selected material can be further explored for its average mechanical properties, atomic structure, slip systems, grain structure, and other properties, as shown in Figure 1.

For example, if the user chooses the metal aluminum, options are available to read further about the face centered cubic (FCC) structure of aluminum. Detailed diagrams, pictures, and explanations are provided to enhance the grasp on the topic. Questions automatically pop-up to stimulate the student into reviewing the educational material. The student is queried as to his/her knowledge of the subject thus far, is provided feedback on areas of weakness, and is prevented from proceeding further until deficiencies are corrected. (See further discussion in the Evaluation and Dissemination Section.)

Once the student has demonstrated sufficient knowledge in the underlying principals involved in the module, the virtual tensile test itself may be started at the selected test speed. A dynamic pointer generates a stress-strain plot in real time as the specimen deforms. The user is prompted throughout the test when, e.g., the yield point, the work hardening region, the ultimate tensile stress, or fracture point are being approached. The user has the option to stop the test at any point and look further into the relationship between the stress-strain state and the micro-mechanisms occurring at that point in time.

Consider, for example, that the yield point is being approached. The yield point describes the boundary between the elastic and the plastic deformation. In some metals (e.g., aluminum), the deviation from the elastic behavior occurs more gradually. While in other materials (e.g., low carbon steel), a sharper yield point and the double yielding phenomena are observed. The basic mechanism of plastic deformation is the motion of dislocations. At this point the user can click on a button describing dislocations. Having a background in dislocations, the user is prompted to read 'elastic-plastic transition', which describes the mechanisms occurring during this stage. Now the user can move on and restart the tensile test. When the work hardening stage is reached, the person can stop the test and fetch details on work hardening.

Thus, we can discuss, within the context of an apparently simple tension test, concepts such as atomic bonding, crystal structure, elastic behavior, plastic behavior, fracture, etc., which have profound implications in the design of structures. Such an approach highlights the importance of the tension test, and the students can better visualize and apply the concepts to designing optimum and reliable structures. After passing through the lectures covering the concepts shown in Figure 1 the students should be in a position to answers questions, a sampling of which is given in the section 'Evaluation of Student Learning'.

Laboratory experiments should be conducted and explained in the context of three important branches, namely mechanics, materials science, and design. Thus a suggested outline for teaching the three subjects in the context of the tension test is given below.

- atomic structure and atomic bonding
- physical and mechanical properties of homogeneous materials and their link with atomic structure and bonding
- constitutive laws for isotropic and homogeneous materials
- need for a tension test
- experimental methods and parameters measured with tension test
- atomic basis for elastic response and effect of atomic bonding
- plastic response of a material:

  - atomic scale deformation mechanisms: dislocations
  - effect of crystal structure
  - effect of microstructure on the plastic response
- fracture:
  - atomic scale fracture mechanisms
  - macro-scale fracture analysis: mode I only.
- effect of stress concentration on the tensile response
- application of tensile test data to total design of axial structures, and using Ashby charts as discussed in Reference 1.

Thus we relate every quantity obtained from a tension test and every region of the stress-strain curve to the atomic- and macro-level mechanisms, which cause that response. This approach helps the engineer in training to understand the complete picture with the linkages between macroscopic response and the atomic deformation mechanisms. It is our belief that this approach will create more informed and creative engineers who can create innovative and reliable structures.

3. Learning Outcomes

Some details of the integrated multimedia enhanced courseware are available at the Web-site http://mmd.sdsmt.edu. More details are available to the students enrolled in the course.

Multimedia courseware described above is intended to increase student learning and teaching efficiency. The courseware is designed so that the students are motivated to learn and use the software with a resulting increase in performance. Careful consideration has been given to the quality of the material in the course so that it is intellectually stimulating and provides positive motivation to learn. According to Russ[4], the students' motivation will be related to their expectation of being able to successfully work through the multimedia package and how they expect to benefit from the process. Hence the instructor has to duly inform the students about the relevance of the courseware and the exercises.

The multimedia courseware promotes active learning by actively engaging the student in the subject matter. This is achieved by using a variety of questions, exercises, and discussions. The courseware has built in questions, problems, and tests, which encourage thinking and action on the part of the student. The interactive capabilities of the multimedia are used to ensure that the student performs the desired learning activity. This is achieved by allowing progress through the package only if the student completes a set of required tasks.

Thus the proposed multimedia courseware facilitates and promotes student learning, and not merely to translate the traditional lecture into a computer environment. It should be noted that the multimedia course does not replace the lecture in its entirety, but supports and enhances this traditional mode of instruction. *In this course, the instructor is not only a transferer of knowledge, but also a facilitator of the student's own learning process.*

4. Evaluation Of Student Learning

Two groups of students were chosen at random. The control group had taken three traditional courses on mechanics, materials science, and design, taught separately and in isolation from one another. The experimental group had taken two of the traditional courses, materials science and design, and was taught the newly proposed integrated course on mechanics, materials, and design, for one semester. Both groups were administered a test which included questions on mechanics, materials, design, linkage between mechanics and design, and between mechanics, materials, and design. The control and the experimental group took the test after they had completed their respective three-course sequence mentioned above. A sampling of the questions, focussed on the linkages, is given below:

- why a material without dislocations is brittle?
- why is an FCC material more suited for colder temperatures than a BCC material?
- why does a low carbon steel display two yield points?
- which metals in the periodic table are more compressible than others?
- how are elastic constants of a material (E and ν) dependent on the shape of the atomic separation vs atomic force curve?
- what are the deformation mechanisms which result in strain hardening behavior?
- what are the possible material choices which possess the best combination of strength, light weight, and low cost, for a vertical rod supporting a heavy weight?
- Which crystal structure results in a more ductile material?
- what are the possible material choices which possess the best combination of strength, light weight, and low cost, for balls in a ball bearing?

The results are shown in Table I.

Table I. Performance of experimental and control groups in the mechanics-material-design diagnostic test.

Question Type	**# of Questions**	**% of Students answering correctly**	
		Control Group (48 students)	**Experimental Group (20 students)**
Materials	4	37	87
Design	2	73	87
Mechanics	7	57	78
Mechanics-Materials link	5	32	61
Mechanics-Materials-Design Link	2	62	78

The results show that students in the control group are definitely weaker in their knowledge of materials science and its application in the design of structures. The limited data from this test also suggests that integrated, or "just in time" teaching, of the three subjects enhances their understanding in each subject. This is borne out by the fact that students in the experimental group performed much better in mechanics, even though the students in the control group had taken a specialized course on mechanics of materials and the experimental group had not taken such a course. However, it should be mentioned that more testing and data collection is necessary to obtain a more conclusive result.

Future evaluation

To reiterate, more testing and evaluation is necessary and is on-going. It is planned that sampling will typically be done at the beginning, middle, and end of each semester. One primary goal of the evaluation will be to obtain feedback that can be quickly implemented. Furthermore, students exiting the new courses emphasizing mechanics-materials links will be tracked in other mechanics courses with regard to their performance, percentage of students using such principles in capstone design projects, undergraduate research, and percentage of students pursing graduate studies in the area of mechanics and materials. Thus, the total impact of the developed curriculum will be known clearly over a span of about 4-5 years.

5. Acknowledgement

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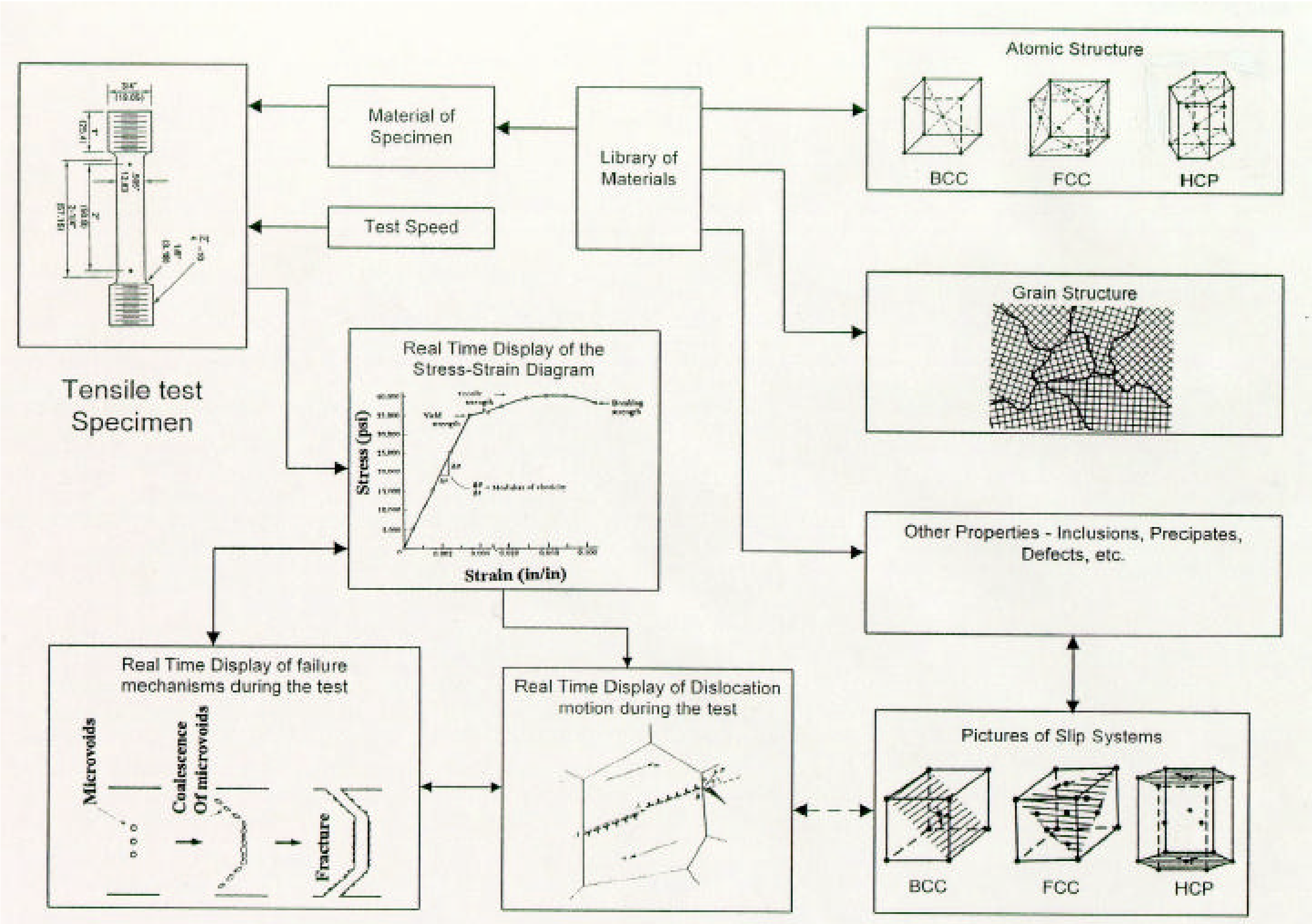

Figure 1: Multimedia based Web page showing the effect of various micro mechanisms and atomic structure during tensile testing of a metallic specimen.