Case Study

A new approach to integrated instruction in mechanics and materials science

S K Khanna[1]*, **C H Jenkins**[2] and **D Roylance**[3]
[1]Department of Mechanical and Aerospace Engineering, University of Missouri–Columbia, Columbia, Missouri, USA
[2]Department of Mechanical Engineering, South Dakota School of Mines and Technology, Rapid City, South Dakota, USA
[3]Department of Materials Engineering and Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Abstract: Educating student engineers in the total design of structures should involve an integrated approach. Hence a new course linking mechanics, materials science and design has been developed. The course, titled 'Mechanics and Materials in Structural Design', educates students in the total design of structures. One important aspect of this approach to teaching is to develop multimedia-based virtual laboratory modules. This paper focuses on one such module, namely the 'tension test of metals' module. This module links the mechanics experiment with the fundamentals of materials science and highlights its usefulness in generating design information. With this approach to teaching, using an apparently simple tension test, the students can better visualize the linkages between mechanics, materials response at the macro and atomic levels, and design. Preliminary evaluation of the course suggests that this philosophy of teaching an integrated course on design is valid.

Keywords: mechanics, engineering materials, multimedia courseware, virtual laboratory, structure–property relationship

1 INTRODUCTION

The principal factors for improvement in the performance and reliability of products are the development of new materials [1], the novel use of existing materials, better understanding of the structure–property relationships [2] and incorporation of both mechanics and materials science in the design of structures [3].

In present engineering practice, structural components are generally designed using the mechanical behaviour of real engineering materials solely in terms of their elastic response. 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 the knowledge concerning the mechanical behaviour 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 behaviour of materials. This approach should be based on the analysis of the underlying unifying principles by which the relevant engineering concepts can be understood and further developed. The unifying principles, by which the apparently complex phenomenological behaviour 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 assump-

---

The MS was received on 21 December 2000 and was accepted after revision for publication on 19 September 2001.

**Corresponding author: Department of Mechanical & Aerospace Engineering, University of Missouri-Columbia, Columbia, MO 65211, USA.*

tions of homogeneity, isotropy and time-independent elasticity are irreconcilable with the phenomena of fatigue and creep of real materials. An analysis of the mechanical behaviour 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 behaviour can be at least qualitatively predicted from knowledge of the internal structure.

The philosophy and methodology of the new course, which assimilates atomic, microstructural and phenomenological materials considerations and links them with mechanics principles, while teaching a broad and integrated course on total structural design, is presented elsewhere [**4**–**6**]. The new course integrates the disciplines of applied mechanics, materials science and design, and enhances the education of undergraduate engineering students. This paper presents an important part of this larger effort, namely multimedia-based development of laboratory modules. It discusses the 'tension test' laboratory module for isotropic metallic materials and describes the deformation response on the basis of atomic and macro level mechanisms.

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

The virtual lab module includes the following:

(a) a multimedia presentation of a tensile testing machine;
(b) a multimedia presentation of the different types of tensile test specimens;
(c) the stress–strain diagram for a ductile metal;
(d) a discussion of the data that can be acquired from a tension test;
(e) a discussion on the evaluation of material properties from the tensile test data;
(f) detailed reviews of the link between atomic structure and materials deformation under the action of external loading (the reviews include topics such as an introduction to the link between atomic structure and materials behaviour, atomic bonding, crystal structure, atomic basis for elastic and plastic deformation and fracture in materials);
(g) drill questions and exercises.

It is believed that this approach will considerably enhance the understanding of material behaviour 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 behaviour and the corresponding mechanisms at the micro and/or atomic level. The importance of inculcating such relationships in the curriculum is also highlighted in references [**7**] to [**9**]. In addition, this courseware facilitates active student learning and reduces reliance on traditional lecture methods of knowledge delivery. Enhanced computer imagery or a multimedia approach has been used to demonstrate the intimate relationships between macroscopic mechanical phenomena and the associated micro mechanisms.

More specifically, the above-mentioned relationships for mechanical behaviours such as elastic deformation, plastic deformation, fracture, etc., in various materials have been investigated. Candidate monolithic materials are metals, ceramics and polymers. However, here only metals will be considered.

As an example, consider a ductile metal (say, aluminium) tension specimen as it is loaded through the elastic and plastic regions to fracture. Typically, such a tension test is done at the middle stages of an undergraduate course. 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, this gap has been bridged.

A schematic flow chart of one such multimedia module, the 'tensile test', is shown in Fig. 1. When a student/user wants to conduct a virtual tensile test experiment, a set of buttons (choices) appears 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 Fig. 1.

For example, if the user chooses the metal aluminium, options are available to read further about the face-centred cubic (fcc) structure of aluminium. Detailed diagrams, pictures and explanations are provided to enhance the grasp of the topic. Questions automatically pop up to stimulate the student into reviewing the educational material. The student is queried as to his or 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 a further discussion in Section 4).

Once the student has demonstrated sufficient knowledge in the underlying principles 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, for example, the yield point, the work hardening region, the ultimate tensile stress (UTS) or

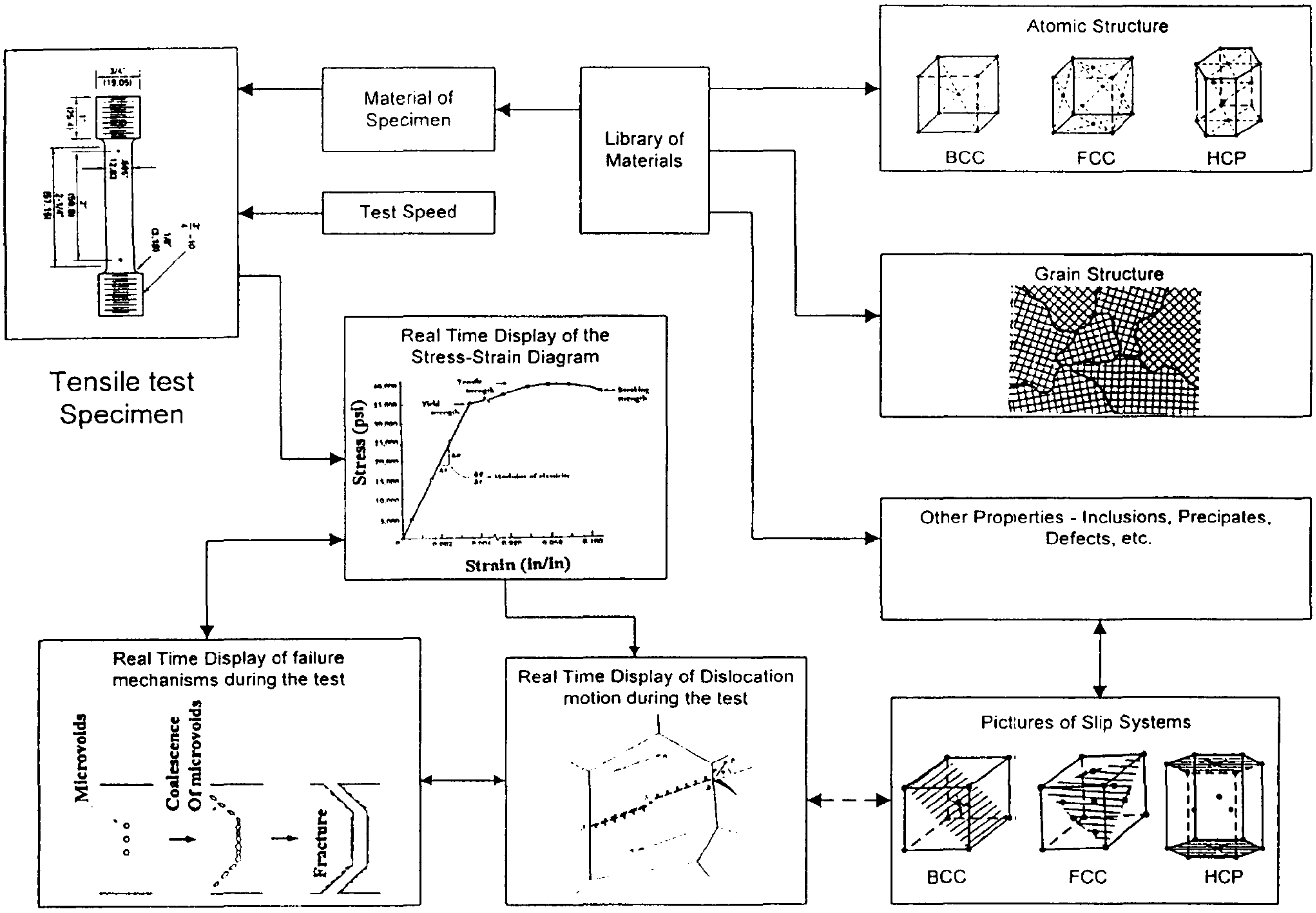

Fig. 1 Schematic of the multimedia 'tension test' virtual laboratory module, showing the effect of various micro mechanisms and atomic structure during tensile testing of metallic specimens

the fracture point is 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. aluminium) the deviation from the elastic behaviour occurs more gradually, while in other materials (e.g. low-carbon steel) a sharper yield point and 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 user can stop the test and fetch details on work hardening.

Thus, within the context of an apparently simple tension test, concepts such as atomic bonding, crystal structure, elastic behaviour, plastic behavior, fracture, etc., which have profound implications in the design of structures, can be discussed. 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 Fig. 1, the students should be in a position to answers questions, a sampling of which is given in Section 4.

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:

(a) atomic structure and atomic bonding;
(b) physical and mechanical properties of homogeneous materials and their link with atomic structure and bonding;
(c) constitutive laws for isotropic and homogeneous materials;
(d) need for a tension test;
(e) experimental methods and parameters measured with the tension test;
(f) atomic basis for elastic response and effect of atomic bonding;

(g) plastic response of a material:

  atomic scale deformation mechanisms: dislocations,
  effect of crystal structure,
  effect of microstructure on the plastic response;

(h) fracture:

  atomic scale fracture mechanisms,
  macro-scale fracture analysis: mode I only;

(i) effect of stress concentration on the tensile response;
(j) application of tensile test data to total design of axial structures, using Ashby charts as discussed in reference [4].

Thus every quantity obtained from a tension test and every region of the stress–strain curve related to the atomic and macro level mechanisms that 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 the authors' belief that this approach will produce 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 Website http://mmd.sdsmt.edu. More details are available to the students enrolled in the course.

Multimedia courseware as 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 [10], 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 term. Both groups were administered a test that included questions on mechanics, materials, design and linkage between mechanics and design and between mechanics, materials and design. The control and the experimental groups took the test after they had completed their respective three-course sequence mentioned above. A sampling of the questions, focused on the linkages, is given below:

1. Why is a material without dislocations brittle?
2. Why is an fcc material more suited for colder temperatures than a bcc material?
3. Why does a low-carbon steel display two yield points?
4. Which metals in the periodic table are more compressible than others?
5. How are elastic constants of a material (E and ν) dependent on the shape of the atomic separation versus atomic force curve?
6. What are the deformation mechanisms that result in strain hardening behaviour?
7. What are the possible material choices that possess the best combination of strength, light weight and low cost, for a vertical rod supporting a heavy weight?
8. Which crystal structure results in a more ductile material?
9. What are the possible material choices that possess the best combination of strength, light weight and low cost, for balls in a ball bearing?

The results shown in Table 1 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 are necessary to obtain a more conclusive result.

Table 1 Performance of experimental and control groups in the mechanics–material–design diagnostic test

		Percentage of students answering correctly	
Question type	Number of questions	Control group (48 students)	Experimental groups (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 students in the experimental group were provided with one chapter of the course content on a compact disc and were asked to perform a self-study of the chapter. They could view and read the chapter in the authorware environment. The survey questions and their impression of the effectiveness of the multimedia-based chapter are shown in Table 2. The ratings scale used was: 1, poor; 2, not very effective; 3, marginally effective; 4, effective; 5, very effective.

The results show that a good majority of the students thought that this way of teaching is an effective approach. However, a smaller but significant percentage does not seem to agree with the effectiveness of the approach. It is believed that this apprehension is due to two reasons. Firstly, they have to be more informed and helped in using this form of self-study, as they are not accustomed to this approach of teaching. Secondly, navigation through the multimedia-based chapter must be absolutely easy—based on the survey there is some need for improvement in this regard.

4.1 Future evaluation

To reiterate, more testing and evaluation are necessary and are on-going. It is planned that sampling will typically be done at the beginning, middle and end of each term. 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 pursuing 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.

Table 2 Results of a survey on the effectiveness of a multimedia-enhanced chapter

	Ratings				
Questions	1	2	3	4	5
Visual effectiveness		1	5	8	
Ease of navigation	1	1	5	6	1
Accessibility to information		2	7	5	
Comparison to hard copy	2	4	5	3	
Effectiveness of Web-based access		1	5	5	
Effectiveness for self-learning	1	3	3	6	1
Convenience/portability		5	3	5	1

ACKNOWLEDGEMENT

The authors acknowledge the support of the National Science Foundation under Grant NSF DUE 9972394. Any opinions, conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

1 **Hack, H.** Structural material trends in future power plants. *Trans. ASME, J. Engng Mater. Technol.*, 2000, **122**, 256–258.
2 **Onck, P. R.**, **Nguyen, B. N.** and **Giessen, E. van der** The linkage between microscopic cavitation damage and macroscopic crack growth. *Trans. ASME, J. Engng Mater. Technol.*, 2000, **122**, 279–282.
3 **Rishi, R.** An interdisciplinary framework for the design and life prediction of engineering systems. *Trans. ASME, J. Engng Mater. Technol.*, 2000, **122**, 348–354.
4 **Jenkins, C. H.**, **Khanna, S. K.** and **Roylance, D.** Linking design with structural mechanics and materials. *Proc. Instn. Mech. Engrs, Part L, Journal of Materials: Design and Applications*, 2001, **215** (L3), 147–154.
5 **Roylance, D.**, **Cohen, K.**, **Jenkins, C. H.** and **Khanna, S. K.** Mechanics of materials: a material science perspective. *Proc. Instn. Mech. Engrs, Part L, Journal of Materials: Design and Applications*, 2001, **215** (L3), 141–145.
6 **Jenkins, C. H.** and **Khanna, S. K.** Linking mechanics and materials in structural design. In ASEE Annual Conference, St Louis, Missouri, 2000.
7 http://www.jwave.vt.edu/crcd/esmmse4984.
8 **Kriz, R. D.**, **Farkas, D.** and **Batra, R. C.** Integrating simulation research into curriculum modules on mechanical behavior of materials: from the atomistic to the continuum. *J. Mater. Educ.*, 1999, **21**, 47–55.
9 **Garcia, C. B.**, **Endo, C. K.**, **Chang, M.** and **Beltz, G. B.** Dislocation models as teaching aids. *J. Mater. Educ.*, 1999, **21**, 149–155.
10 **Russ, R.** Creative training styles: finding the right fit. *Training Devel.*, **48** (6), 46.