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# **AC 2011-1159: COMPREHENSIVE COURSE REDESIGN: INTRODUCTION TO THE MECHANICS OF MATERIALS**

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# Comprehensive Course Redesign: Introduction to the Mechanics of Materials

## Abstract

Convergence of multiple patterns necessitates significant new directions in redesigning and teaching courses in the area of solid mechanics for undergraduate engineering students.

- Growing applications of polymeric, biological, and geological materials
- Promising approaches to teaching
- Key differences in behaviors of polymers and biological materials when compared with traditional engineering materials like steel, concrete, and wood
- Lack of understanding of more than one measure of stress and strain and their Relationships to different failure criteria.
- Packed Courses

Together, these patterns require that the mechanics community identify and advocate new approaches to teaching undergraduate solid mechanics. New approaches to course design and teaching are required to address these multiple challenges.

One opportunity for course redesign is the mechanics of materials course taken by sophomore or junior mechanical engineering students, which is a pivotal course in undergraduate curricula for mechanical engineering students. In redesigning the course, the faculty member that redesigned the course identified a set of learning outcomes by focusing on core ideas for the course and then used Bloom's taxonomy to articulate three different levels of achievement:

- Level of Achievement
  - Calculate/identify
  - Apply/analyze
  - Evaluate/design
- Core Course Ideas
  - Functional decomposition to craft design requirements for mechanical components
  - Concept of failure and material transitions (yielding, fracture, buckling)
  - Stress
  - Strain
  - Stress versus strain behavior (elasticity) and stress versus time and strain versus time (viscoelasticity)
  - Multi-axial loading behavior
  - Behavior of specific common geometries (e.g., beams, thin wall objects)

With learning outcomes established, the faculty member that taught course reorganized the course material around a set of five prototypical problems. For each problem, the faculty member presents a scenario within the context of a realistic design challenge, ambiguous desired outcomes, and a vague collection of constraints. Then, students offer ideas on how to approach defining a problem, generating alternatives, and identifying key mechanics concepts that will play a role in the solution.

Assessment is based on quizzes, in-class examinations, in-class presentation of mechanics concepts by student teams, and a final examination. On quizzes and exams, each question corresponds to a core course idea and a level of achievement. Course grades are assigned based on patterns of demonstrated learning with respect to a table of core course ideas and levels of achievement. For example, an “A” could be earned if the student demonstrates level 3 achievement (evaluate/design) for at least four core course ideas.

## Introduction

Convergence of multiple patterns necessitates significant new directions in redesigning and teaching courses in the area of mechanics of solids.

- **Growing Application of Polymeric, Biological, and Geological Materials:** Polymers and polymer-based composites have extensively replaced metals, metal-matrix composites, and even materials such as asphalt and concrete in many applications. Global annual production of polymers (by weight or volume) is greater than that of all metals. In order to describe polymeric and biological materials, and furthermore describe geological materials, mechanics of solids must expand its scope to encompass these materials and must advance its methodologies to apply to these materials.
- **Promising Approaches to Teaching:** Innovative methods for course redesign and teaching approaches have solid empirical evidence to support their influences toward improved learning. Promising practices that are relevant to redesign of undergraduate courses in mechanics of solids include emphasis on learning outcomes, use of inquiry-based teaching approaches that organize course content around challenges, assessment approaches that emphasize both qualitative understanding and quantitative application of concepts, teaching approaches including both collaboration and individual accountability, and formative feedback on student learning.
- **Key Differences between Behavior of New and Traditional Materials:** Characterization of the mechanical behavior of polymeric, biological, and geological materials, and even metals, especially materials such as superplastic alloys, requires concepts and tools quite different from those which describe the elastic response of metals. Despite the ubiquity of polymers and polymer-based composites and the growing importance of understanding biological materials, small-deformation theories fashioned to deal with the response of metals remain a focus of the traditional, undergraduate courses in mechanics of solids, with the exception of special purpose electives on polymers, composites, or biological materials.
- **Missed Connections between Failure Modes and Stress and Strain:** Students who take the course in which stress and strain are defined as the starting point for the course may fail to discern that they calculate stress and/or strain to gain insight about the proximity of a component, with the specified external forces, to failure.
- **Packed Courses:** Adding relevant content for polymers, polymer-based composites, biological materials, and geological materials to metals-appropriate content of a traditional mechanics of materials course will fill multiple courses.

Together, these patterns require that the mechanics community identify and advocate new approaches to teaching undergraduate mechanics of solids. New approaches to course design and teaching are required to address these multiple challenges.

One opportunity for course redesign is the mechanics of materials course taken by sophomore or junior mechanical engineering students, which is a pivotal course in undergraduate curricula for mechanical engineers. At Texas A&M University, the mechanics of materials course is CVEN 305 Mechanics of Materials. Although it is required for biological and agricultural, civil, mechanical, ocean, nuclear, and petroleum engineering students, course redesign focused on mechanical engineering students. For these students, the undergraduate catalog suggests the course be taken in the second semester of the sophomore year. The sole prerequisite course is MEEN 221 Statics and Dynamics. The catalog suggests that MEEN 222 Materials Science be taken in the first semester of the sophomore year, but MEEN 222 is not a prerequisite for CVEN 305.

The paper describes redesign of a mechanics of materials course to focus on design and failure prevention and experiences in offering the redesigned course for three semesters: fall 2009, spring 2010, and fall 2010. Redesign follows the framework suggested in Wiggins and McTighe<sup>1</sup>:

- First, develop the learning outcomes for the course. Learning outcomes state expectations for learning in terms of what students will be expected to demonstrate.
- After the learning outcomes are developed, the faculty member designs the plan through which student achievement of the learning outcomes will be assessed and evaluated.
- Finally, after the assessment plan is developed, the faculty member designs the learning activities and content delivery that will support student development with respect to the learning outcomes.

## Background

### *Case for Concept/Content Redesign for the Introduction to the Mechanics of Materials*

Characterizing behavior of polymeric materials requires concepts and tools quite different from those introduced to describe the response of metals. For instance, while a metal cylinder will expand when heated, leading to the terminology “the coefficient of linear expansion,” elastomeric materials often contract when heated. Basic notions such as those of stress and strain have to be re-examined since polymeric materials can undergo very large deformations, well beyond the point of “yielding” that is found in many metals. Since the failure of bodies depends on the stresses to which they are subjected, a clear understanding of the meaning of “stress” is necessary when discussing such materials. Consider, for instance, the deformation of a cylinder. Stress is usually defined as force acting per unit reference cross-sectional area. If the cylinder is metal or concrete, then the cross-sectional area does not change significantly; however, if the cylinder is polymeric, deformation in which the cross-section of a cylinder of polymeric material becomes half its original area makes this definition of stress imprecise. We then need to know when we use the term stress, whether we are referring to the force acting per unit reference area, namely the Lagrangian or Piola-Kirchhoff stress or whether we are referring to the force per unit deformed area, namely the Eulerian or Cauchy stress. Further, students need to learn whether failure will be most directly related to the Lagrangian or Eulerian stress, and more importantly, what evidence could help them decide which notion of stress would be more indicative of potential material failure. While these two ideas of stress could be very similar for metals, there could be very large differences for polymers or polymer-based composites.

Similarly, consider the uniaxial response of a cylinder of polymeric material that has been elongated due to the application of an axial load to twice its length. By strain, we usually mean Lagrangian strain, strain per unit reference length (usually the reference configuration is the initial or undeformed configuration). The Eulerian strain is the strain per unit current length. These two concepts are often given the somewhat dubious titles of “engineering” and “true” strain, respectively, as if engineering strain is somehow “untrue.” For metals, under normal operating conditions, these two measures of strain are nearly the same. However, in the case of polymers these two measures of strain could differ by several hundred percent. In order to understand the failure of polymeric materials one needs to know which of these stresses or strains are being considered. For polymers, we need to know which notion of strain is most closely related to failure of the cylinder under load.

Another example that points to inadequacy of current texts on deformable body mechanics is the notion of Poisson’s ratio. This notion is quite well understood within the context of metals and refers to the lateral contraction that takes place due to the elongation of a body. However, it has very limited applicability to polymeric materials— it has relevance only to very small strains and restricted to the elastic response of polymers (as such materials are viscoelastic). In fact, polymeric materials give one reason to question notions that seem to be a matter of common sense: such materials can even expand when extended, i.e., it is possible that the Poisson’s ratio can be negative.

Another reason to redesign the mechanics of materials course is that traditional courses do not consider time-rate dependent behavior of materials. They tend to model bodies as being linearly elastic, thereby being characterized by two material constants, the Young’s Modulus and Poisson’s ratio, in the case of isotropic materials. Many real materials are not purely elastic. In fact, most polymeric materials are viscoelastic. It is important to recognize that polymeric materials can “stress relax” and “creep.” Stress relaxation is the phenomenon wherein the force necessary to maintain a fixed elongation reduces with time. Creep refers to the phenomenon of continued elongation due to the application of a fixed force. These two phenomena are typically not accounted for in a traditional mechanics of materials course.

Students taking mechanics of materials must understand the essential reason that stress and strain are calculated – because they indicate how close the object is to failure. Explaining this connection is vital to understanding that stress and strain are more than “numbers to be calculated.” However, even the notion of failure may change when the range of materials considered expands from metals to polymers. Consider a load-lifting device such as a steel chain or cable. In this case, yielding of the steel is considered failure, but there can also be unforeseen catastrophic failure under certain conditions even at loads far below where yielding would be predicted. On the other hand, a sling made from a polymer such as Kevlar could fail due to overload, yet undergo extremely large deformations while continuing to support the load as the sling slowly elongates until the load reaches the floor. This example reinforces the importance of carefully defining failure, stress, strain, and their relationships. Also consider the design of a polymer garbage or grocery bag, an object used every day. One needs to recognize that the strain will by no means be infinitesimal as commonly assumed in load-bearing metallic members, and such bags in fact are intentionally designed to exhibit inelastic response. Another application

wherein the large deformation of the body under consideration has to be taken into account is that of automobile tires. A significant portion of the energy consumption of an automobile is due to deformations of the tires. Moreover, in order to ensure that tires do not fail, one needs to take into account the fact that deformations could be large. Such issues are of immense importance in avoiding catastrophic tread separation, as evidenced by the fatalities preceding the vast Firestone tire recalls several years ago. These examples reinforce the importance of carefully defining failure as well as the notions of stress and strain and their relationships to failure. Students taking mechanics of materials must be able to start from a scenario and carefully reason from performance expectations and constraints, decide an appropriate interpretation of failure, and select appropriate applications of stress and strain. These issues are not raised in most current courses on mechanics of materials.

Even metals, when subject to sufficiently large loading as in metal forming and other applications, undergo “plastic” response and suffer permanent set. Depending on the load and the particular metal in question, the body under consideration can undergo large deformations and the “small strain” theories presented in most widely-used textbooks are inadequate. Dr. Stoughton, GM Technical Fellow at the General Motors Research and Development Center, in a letter supporting this effort, emphasized this need when he stated that the “challenge of the evolution of anisotropy with nonlinear plastic deformation is poorly understood by most graduating engineers.” (Note: The entire support letter can be found in the appendix.) The situation for polymers is much more drastic. Even at modest loads, a polymeric body typically exhibits viscoplastic response.

Many of these concerns about inert polymeric materials also apply to the mechanics of biological materials. Ligaments, tendons, vascular walls, and other parts of the body are subject to finite deformations. Polymeric biodegradable stents can undergo deformations of several hundred percent. In these cases, concepts presented in standard texts in mechanics of materials are grossly inadequate. As the fields of biomedicine and mechanobiology become increasingly important, an undergraduate text that addresses basic issues concerning the mechanics of biological materials becomes even more necessary.

While the need to integrate design into the curriculum has been well recognized, efforts to inject it into the curriculum have been primarily made only at the freshman and senior levels, the latter where students work on capstone design projects. Sophomore and junior level courses often do not develop knowledge and abilities of students with respect to the engineering design process. However, the mechanics of materials course represents an excellent opportunity to simultaneously develop abilities for analyzing material failure and abilities to connect failure analysis to the engineering design process. Engineering design provides a cornerstone of the proposed approach to the redesign of the mechanics of materials course.

#### *Prior Research on Mechanics of Materials Course Developments*

In their survey of prior research on the introductory course in deformable mechanics, the authors found that much of the work on innovations in mechanics of materials education concentrated on developing instructional materials (primarily computer-based) that helped students visualize complex interactions among forces, stresses, strains, and deformations<sup>2-10</sup>. Two examples were

found in which the professors organized material around design problems<sup>11, 12</sup> however, the authors did not find prior work that attempted to rethink the conceptual content of material to accommodate the spectrum of materials engineering graduates will use in designs in the future.

### Learning Outcomes

In redesigning the course, the faculty member that redesigned the course identified a set of learning outcomes by focusing on core ideas for the course and then used Bloom’s taxonomy to articulate levels of achievement. He started with the six levels of learning presented in the Revised Bloom’s Taxonomy<sup>13</sup>. For simplicity, he collapsed two adjacent levels of learning into a single level of achievement. As a result, the course describes three levels of achievement:

- Calculate/identify (corresponding to the Remembering and Understanding levels of learning in the Revised Bloom’s Taxonomy)
- Apply/analyze (corresponding to the Applying and Analyzing levels of learning)
- Evaluate/design (corresponding to the Evaluating and Creating levels of learning)

With respect to course content, the faculty member developed the following core course ideas:

- **Functional decomposition:** This core idea focuses on design methodology skills that are essential to connect real-world performance to fundamental engineering concepts. Functional decomposition involves the process of examining an open-ended design challenge and identifying specific and discrete engineering requirements that must be satisfied by any possible solution to the challenge.
- **Concepts of failure and material transitions (yielding, fracture, buckling):** This core idea focuses on material failure and its prevention. The faculty member emphasizes qualitative understanding. Students are expected to be able to describe how different transitions represent modes in which a component can fail or can become useful. Then, for a specified situation, they are expected to determine the relevant failure modes.
- **Stress:** Stress is introduced as an indicator of how close a material is to relevant transitions (whether they represent failure or a useful behavior). In this way, students are expected to apply ideas that calculating stress for a specified situation provides indication of how close a specified material is to undergoing a transition in a specified situation.
- **Strain:** Strain is also introduced as an indicator of how close a material is to relevant transitions.
- Stress versus strain behavior (e.g., elasticity) and stress versus time and strain versus time (e. g. viscoelasticity)
- Multi-axial loading behavior
- Behavior of specific geometry (e.g., beams, thin wall objects)

With the core course ideas and the three levels of student achievement, a 7 x 3 table for the course learning outcomes is created (see Table 1).

Table 1. Course Learning Outcomes

	Level 1: Calculate/identify	Level 2: Apply/analyze	Level 3: Evaluate/design
Functional decomposition			
Concept of failure and material transitions			

(yielding, fracture, buckling):			
Stress			
Strain			
Stress versus strain behavior (e.g., elasticity) and stress versus time and strain versus time (e. g. viscoelasticity)			
Multi-axial loading behavior			
Behavior of specific common geometries (e.g., beams, thin wall objects)			

With this table, there are 21 course learning outcomes-level combinations. The assessment plan described in the next section describes how achievement of these learning outcomes is used to determine course grades.

### Assessment Plan

The assessment plan has been structured such that there is a direct correlation between the learning outcome-achievement level combinations and the final course grade. This is achieved by structuring assessments with respect to the 21-cell table shown in Table 1. For example, the student understanding of Learning Outcome 3: Stress, is assessed with respect to the three levels of achievement:

- a) Can the student identify the concept or perform a simple calculation using it?
- b) Can the student look at a mechanical scenario and decide which concept to apply, and perform multiple related calculations to determine an answer?
- c) Can the student evaluate a given scenario, often open-ended, where the concept may be only one part of a complex system involving other concepts?

At the completion of the semester, each outcome-level cell in the matrix contains a score that represents the student’s demonstrated understanding of the particular outcome at the respective achievement level. Possible scores within a cell follow a five-point ordinal Likert-type scale with a score of 4 representing that the student has demonstrated excellent understanding, down to a score of 0 representing no understanding whatsoever at that level. An outcome-achievement cell is considered ‘accomplished’ if a student receives a score of 3 or higher in that cell.

Multiple-choice and calculation quizzes are administered to evaluate the lower two levels of achievement for each core course idea: calculate/identify and apply/analyze. Each quiz question is tied to a particular outcome-level combination, and multiple questions throughout the semester assess performance with respect to that combination. Quizzes are administered outside of class time using the campus-wide online learning environment system (eLearning). Each quiz question is scored on the five-point scale described above. During the course of the semester, students can monitor their level of understanding of each learning outcome by examining their scores in each of the outcome-level cells in the overall grading matrix. The final score used in each outcome-level cell is calculated by taking the median of the individual scores earned for each associated quiz problem.



Assessment of student grasp of the highest achievement level, evaluate/design, of the learning outcomes is done through the use of a comprehensive final examination. Because of the more complex nature of this achievement level, assessment cannot be reliably made using a calculation-based quiz as is done at the lower two achievement levels. Final examination questions are somewhat open ended and present scenarios that integrate multiple learning outcomes while challenging students to consider prioritization of learning outcome concepts, explanation of their reasoning, and decision making based on appropriate calculations. Exam grading is accompanied by a detailed rubric that shows that appropriate score (0 through 4) for the student's response.

The grading method for the course involves a tally of the successfully accomplished (score of 3 or above) learning outcome-achievement level cells in the grading matrix. For recent course offerings, the follow scheme was used to assign the course grade based on achievement of the twenty-one learning outcomes-level combinations. Students receive a grade of

- 'A' if they accomplish at least four (out of seven) core course ideas at the evaluate/design level.
- 'B' if they accomplish at least four (out of seven) core course ideas at the apply/analyze level.
- Lower grades are given for lower tallies.

The utility of this grading approach is in the fact that students performing poorly during the semester can take steps to improve their grade so long as they demonstrate higher-level understanding of the learning outcomes at the time of the final exam. Other instructors who wish to adapt this general approach could modify relationships between the accomplishment of the twenty-one learning outcome-level combinations and the course grade based on instructor beliefs and/or preferences as well as institutional guidelines.

## Course Design

With the learning outcomes established and the assessment plan designed, the faculty member that taught the course reorganized course material around a set of five prototypical problems.

- **Prototypical Problem No. 1:** Students are given the responsibility of designing components in a prosthetic knee joint using a four-bar mechanism. After initial determination of functional requirements for a solution, students decompose the problem further to determine which material transitions (yielding, buckling, viscoelastic response, etc.) are central to the proper performance of the design. This gives the students an immediate indication of the relevance of course content rather than initially presenting the concepts and trying to make a case for why they are important.
- **Prototypical Problem No. 2:** Students serve on a design team for a lower-leg prosthetic, and must consider the functional requirements and potential transitions involved in the tibial column of the prosthetic as it experiences compressive stress. Students should consider parameters that affect buckling, as well as how these parameters may cause tradeoffs against other requirements such as cost and weight of the component.
- **Prototypical Problem No. 3:** In order to show students the relevance of stress transformations in multi-axial loading, a third problem challenges students with the design of a stabilizing rod for a spinal fixation device that experiences axial loads,

bending, and torsion. Students must again consider functional requirements, as well as the ability to determine failure when a complex loading situation is encountered. The concept of failure criteria is introduced as part of this problem.

- **Prototypical Problem No. 4:** The Poisson effect is involved in the fourth prototypical problem, which involves students determining functional requirements for a material used in dental implants. The students are challenged with determining how the implant stem, which is the component that is affixed within the jaw and anchors the implant, could lead to fracture of surrounding bone due to compressive loads applied to the bite surface of the tooth.
- **Prototypical Problem No. 5:** Students revisit a dental topic in the fifth problem as they play the role of material designers in identifying requirements and selecting candidate materials for dental fillings. The problem illustrates how thermoelasticity leads to the eventual failure of metal amalgam dental fillings due to temperature swings within the mouth during eating.

All of the problems are biomedical applications. This selection was intentional, since the faculty member thought that biomedical applications would connect with diverse populations and backgrounds of students, since all students could identify with the application. One drawback of the current set of problems is that they do not illustrate the breadth of applications of the course content. However, some of these applications are illustrated in homework, quiz, exam, or example problems.

For each problem, the faculty member presents a scenario within the context of a realistic design challenge, ambiguous desired outcomes, and a vague collection of constraints. Then, students offer ideas on how to approach defining a problem, generating alternatives, and identifying key mechanics concepts that will play a role in the solution. Here is an example of the problems that have been presented in the course:

This approach to course development in which the course is organized around a carefully selected set of prototypical problems or challenges was used throughout the VaNTH Engineering Research Center<sup>14-16</sup>. The Center based its approach to course development and teaching on *How People Learn*<sup>17</sup> and the STAR.Legacy Cycle<sup>18</sup>. “Every Legacy Cycle (Schwartz et al., 1999) begins with a challenge. Following this challenge, learners journey through five steps of the Legacy Cycle. These include: (1) generating preliminary ideas about the challenge, (2) obtaining information from experts representing multiple perspectives on the challenge, (3) conducting additional research and revising their preliminary ideas about the challenge, (4) testing their understanding of key principles by solving problems (receiving formative feedback), and (5) completion of a transfer task and sharing their results with their peers”<sup>15</sup>. Roselli and Brophy (2006), in comparisons over a “three-year period between student performance on knowledge-based questions in courses taught with taxonomy-based [traditional] and challenge-based [VaNTH] approaches to instruction,” found that “students in CBI [challenge-based instruction] classes performed significantly better than students in control classes on the more difficult questions (35 percent versus four percent).” The proposed approach is also similar to problem-based learning approaches that were first developed in medical schools<sup>19</sup>, but now have been applied to many different disciplines<sup>20</sup>. Studies of problem-based learning show positive influences on student learning, especially performances associated with more challenging

cognitive levels<sup>21-27</sup>. Also, the approach resembles guided inquiry learning in which the teacher starts with a question to be addressed and initial student responses to the question to guide the inquiry process to a resolution of the question. Guided inquiry learning is the basis for the Process-Oriented Guided Inquiry Learning<sup>28</sup> project in chemistry, which has developed materials for using the approach in several different chemistry courses. This guided inquiry approach to teaching chemistry has shown promising improvements in student learning and success<sup>29, 30</sup>. Context, offered through initial presentation of a challenge in each course segment will help all students, including students from groups underrepresented in engineering, more ways to identify with and establish connections to the material. In summary, there is substantive evidence supporting the problem-based approach being used to teach this version of a mechanics of materials course.

Assessment is based on quizzes, in-class examinations, in-class presentation of mechanics concepts by student teams, and a final examination. On quizzes and exams, each question corresponds to a core course idea and a level of achievement. Course grades are assigned based on patterns of demonstrated learning with respect to a table of core course ideas and levels of achievement. For example, an “A” could be earned if the student demonstrates level 3 achievement (evaluate/design) for at least four core course ideas.

### Student Reactions

The approach to assessment and grading is radically different than a total points system in which grades are assigned based on acquisition of percentages of total points, e.g., student earns an A if the percentage is 90% or above; students earns a B if the percentage is 80% or above, and so on. One reason the faculty member implemented the assessment and grading system was to help students focus on expected outcomes and to help them track achievement of these different outcomes. Since the system was so different, the faculty member was concerned about student perceptions. Anecdotal comments from students suggested that the system did help them keep abreast of how their learning was progressing. Many students have expressed satisfaction with being able to determine both where they are with respect to their grade in the course and what they need to work on to improve their grade. Some students have expressed confusion with the approach to grading because it is so different compared approaches that they have seen in previous courses. Here are some sample comments:

- The grading system was confusing
- Grading has been consistent but the 0-4 system is aggravating because my mind has been trained to think on the 0-100 scale
- It was fair and intuitive, but the system seemed a little unpredictable at times
- It was very strange, but fair. Might want to reconsider how it's done, but I suppose it does offer students multiple chances to do well.
- Unique grading scale. Overall I like it.
- Felt grading policy was good.

On the student course evaluation at the end of the semester, students were asked to respond to the following item:

- Grading has been fair and consistent. Circle Yes or No

Here are the results:

- Fall 2009: 21 Yes, 9 No
- Spring 2010: 23 Yes, 8 No
- Fall 2010: 29 Yes, 1 No

Feedback has encouraged the faculty member to keep the system for future course offerings.

### Student Mastery of Course Content

One advantage of the assessment and grading system is that the faculty member can easily track areas of student achievement or the lack thereof. For the course offered in the fall 2010 semester, Tables 2 and 3 shows the percentage of students demonstrating achievement of each level for each of the seven core course ideas during the past two semesters.

Table 2. Course Learning Outcomes and Student Learning  
Spring 2010

	Level 1: Calculate/identify	Level 2: Apply/analyze	Level 3: Evaluate/design
	Percentage of students demonstrating achievement of this level.	Percentage of students demonstrating achievement of this level.	Percentage of students demonstrating achievement of this level.
Functional decomposition	92%	92%	100%
Concept of failure and material transitions (yielding, fracture, buckling):	55%	67%	59%
Stress	29%	39%	47%
Strain	65%	73%	33%
Stress versus strain behavior (e.g., elasticity) and stress versus time and strain versus time (e. g. viscoelasticity)	67%	57%	88%
Multi-axial loading behavior	67%	43%	24%
Behavior of specific common geometries (e.g., beams, thin wall objects)	27%	53%	10%

Table 3. Course Learning Outcomes and Student Learning  
Fall 2010

	Level 1: Calculate/identify	Level 2: Apply/analyze	Level 3: Evaluate/design
	Percentage of students demonstrating achievement of this level.	Percentage of students demonstrating achievement of this level.	Percentage of students demonstrating achievement of this level.
Functional decomposition	90%	75%	15%
Concept of failure and material transitions (yielding, fracture, buckling):	68%	75%	28%

Stress	68%	55%	15%
Strain	45%	70%	0%
Stress versus strain behavior (e.g., elasticity) and stress versus time and strain versus time (e. g. viscoelasticity)	63%	58%	8%
Multi-axial loading behavior	88%	65%	23%
Behavior of specific common geometries (e.g., beams, thin wall objects)	50%	35%	20%

Remember that students can demonstrate achievement of levels 1 and 2 on in-class quizzes, but can only demonstrate achievement of level 3 on examinations during the semester and in the final. Generally, the percentage of students demonstrating achievement declines as the level increases, particularly level 3. Achievement of level 3 outcomes, particularly for the last two core course ideas, is receiving attention as the next iteration of the course is being implemented in spring 2011.

#### Performance in Subsequent Courses

There are two required mechanical engineering courses in the area of mechanics of solids for which the mechanics of materials course is a prerequisite: (i) Materials and Manufacturing Selection in Design and (ii) Solid Mechanics in Mechanical Design. However, at this time, students had taken only one of the two courses in sufficient numbers to look for differences, i.e., Materials and Manufacturing Selection in Design. When comparing grades in this course for the group of students who had taken the redesigned version of mechanics of materials with grades for the students who had taken the existing version of the course, there was no significant difference in the grades. At this point, a significant redesign intended to support students in learning to analyze both metals as well as polymers and other materials has not harmed student learning in a subsequent course. The authors regard this as a positive finding.

#### Conclusions

A mechanics of materials course has been redesigned using problem-based learning to enable students to work with a larger range of materials than traditional mechanics of materials courses. Evaluation of the redesign is preliminary at this stage. More data on student performance in downstream courses needs to be collected and analyzed.

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## Appendix

The support letter from Dr. Thomas B. Stoughton, GM Technical Fellow, General Motors Research and Development Center, was included at the request of a reviewer.



May 9, 2008

 **General Motors**

**GM R&D and  
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Prof. K. R. Rajagopol  
Forsyth Chair in Mechanical Engineering  
Texas A&M University

Dear Professor Rajagopol,

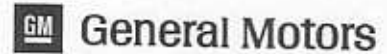
I am delighted to hear that you are planning to develop a new undergraduate sophomore level course on mechanics of materials to cover the broad range of materials of interest to the manufacturing industry, and eventually use this material in a new textbook. In my experience, graduating engineers and material scientists at both the undergraduate and advanced degree level, have an inadequate level of understanding to meet the challenges in today's highly competitive manufacturing environment, caused not just by the merging of markets on a global scale, but the impending environmental challenges that result from the rapidly increasing industrialization and increase in energy consumption worldwide. This need, combined with your characteristic heuristic style to explain complex phenomenon to the student, I believe are the two essential ingredients in the making of a valuable new course in material science.

In addition to the point you raised about the applicability of existing textbooks to support courses on the mechanics of polymer, polymer composite, and biological materials, I believe it is also important to present a more realistic picture of metals than is treated in existing textbooks, in order to give our engineers a broader perspective and understanding of the challenges they will face in their careers, whether they work for industry directly, or support industry needs in their research at academic institutions. In my opinion, textbooks focus too heavily on the assumption of isotropy, and discuss anisotropy only as a special case, when in fact, the opposite is true. The textbooks also focus too much attention on isotropic hardening, or simple kinematic or mixed hardening, both of which are only valid for linear or unidirectional loading, respectively, which in fact is rare in most manufacturing and product performance simulation that are dependent on the manufacturing history. Because of this emphasis, the challenges of dealing with anisotropy, especially the challenge of the evolution of anisotropy with nonlinear plastic deformation, is poorly understood by most graduating engineers. (And I am talking about metals, not polymers, where the assumption of isotropy is even less justified.)

A model that exemplifies the importance of understanding these issues is the challenge of understanding the crash performance of a steel fuel tank, taking into consideration the manufacturing history of the components, including progressive forming in multiple stages and possible additional hardening of the product after stamping by heat treatment. The challenge of constitutive models to predict the complex response under nonlinear manufacturing processes and then determine the product performance including prediction of fracture is far beyond the capability of existing constitutive models and is insufficient to meet the need of industry to reduce or eliminate reliance on physical tests.

In addition to the challenge of predicting formability in manufacturing and deformability in product performance, industry is also looking to use material models to accurately predict springback or changes to the product shape from elastic (or elastic-plastic) unloading of the forming stresses required to stamp the part by the tool, in order to compensate the shape of the tool so that the metal "elastically" unloads to the desired

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product shape. Errors in springback prediction are known to be attributed to two limitations of existing constitutive models, 1) failure to reliably predict forming stresses under nonlinear loading conditions, and 2) neglect of what are observed to be significant changes to the "elastic" modulus during unloading, as a function of plastic strain. Apparently, Hooke's Law is not valid throughout a deformation that involves plasticity. What page of any existing textbook covers that issue?

Beyond the traditional issues, new materials for light-weighting, like aluminum, magnesium and advanced high-strength steels, as well as metal composites, and new processes required to manufacture them, like higher temperatures, or higher rates or processes like electromagnetic forming, or special heat treatments during the manufacturing process are proposed. Due to limitations of existing constitutive modeling in these technological areas, development and use of these new materials and processes are hampered by the need for and reliance on physical tests.

I would be honored to serve as an advisor during the development of your course and to provide feedback and suggestions to increase its relevance to the automotive manufacturing engineer. And although I have an automotive perspective, the issues faced by the automotive industry are common to most manufacturing industries and to the general application of constitutive modeling technology to industry. Although I have 25 years of experience with General Motors Research Lab working in metal forming technology, I believe you know that I am also a physicist by training, with a Ph.D. in high energy physics from MIT, and a BS in physics from Caltech. I believe that this background in the physical sciences, plus my practical experience in research and development of metal manufacturing technology, gives me an unusual and valuable perspective to evaluate a sophomore level course in constitutive modeling. In addition, one of my assets that has helped me in my own research, which I think would serve well in the development of a textbook in engineering science, is that I have trained myself to be aware of and question my assumptions. You may find this characteristic a bit annoying, if I feel your treatise makes statements that are too broad, or I feel they may be taken out of the context that you intended to limit them, but I suspect that you will find my advice regarding clarification of assumptions to be of value to the students that you want to educate with your course.

Sincerely,

Thomas B. Stoughton

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