AC 2008-2056: HUMAN BONE SOLID MECHANICS CHALLENGE: FUNCTIONALLY GRADED MATERIAL STRUCTURE WITH COMPLEX GEOMETRY AND LOADING

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Human Bone Solid Mechanics Challenge: Functionally Graded Material Structure with Complex Geometry and Loading

Abstract

This paper presents a series of solid mechanics challenges that are being developed to reinforce solid mechanics concepts and to illustrate the relationship between classical mechanics of solids and finite element stress analysis while highly motivating students. The challenges are being developed through an interaction with VANTH, an NSF funded Engineering Research Center for Bioengineering Educational Technologies, that introduced the authors to the How People Learn framework for the design of effective learning environments and challenge/problem based learning module development. The authors have supplemented the HPL theory with explanations of the Legacy learning cycle from a new point of view and with new implementation ideas. To reinforce solid mechanics concepts and to illustrate the relationship between solid mechanics analytical solutions and numerical solutions, the authors are developing a series of challenges that use web-based games and the involvement of students in the game design process, combined loading bone problems and the involvement of students in learning through teaching, the concept of functionally graded material structures and their potential applications, and the challenges faced in the analysis of graded materials with complex geometries. The objectives of the challenges include reinforcing students' understanding about solid mechanics and the difference between analytical and numerical solutions, and fostering students' interest in the finite element stress analysis for design and research. According to the authors, students are motivated to learn when they understand the connections between the subject matter and their interests, values, goals, and career aspirations and that long term success may depend upon their ability to access and apply what they have learned. The first challenge can be utilized in High School physics courses with the remaining challenges appropriate for undergraduate college level instruction in solid mechanics and introduction to Finite Element Analysis. Challenges contain screen capture movies, computer games, and materials developed by undergraduate students. Furthermore, the initial impact of the challenge on the students and on the solids mechanics course is described. The challenges integrate course content across discipline boundaries and help students build connections between related and seemingly unrelated concepts. The challenges demonstrate to students that their education is the process of building an integrated knowledge base that will ultimately prepare them for applying that knowledge in their career.

Introduction

This paper presents a series of solid mechanics challenges that are being developed to reinforce solid mechanics concepts and to illustrate the relationship between classical mechanics of solids and finite element stress analysis while highly motivating students. The challenges are being developed through an interaction with VANTH, an NSF funded Engineering Research Center for Bioengineering Educational Technologies, that introduced the authors to the How People Learn[1] (HPL) framework for the design of effective learning environments and challenge/problem based instruction. The challenges are based on the STAR Legacy learning cycle[2,3]. The authors have supplemented the HPL theory with explanations of the Legacy learning cycle from a new point of view and with new implementation ideas. The author's contributions to the Legacy learning cycle and the focus of the solid mechanics challenges are discussed in this section.

First, a brief description[2] of the Legacy learning cycle as described by it's developers is paraphrased below.

Look ahead: The learning task and desired knowledge outcomes are described here. This step also allows for pre-assessment and serves as benchmark for self-assessment in the Reflect Back step.

Challenge 1: The first challenge is a lower difficulty level problem dealing with the topic. The student is provided with information needed to understand the challenge. In the engineering design process, this is the stage of problem definition. The steps shown below represent the remainder of the cycle, which prepare the students to complete the challenge.

a. Generate ideas: Students are asked to generate a list of issues and answers that they think are relevant to the challenge; to share ideas with fellow students, and to appreciate which ideas are new and to revise their list. In the engineering design process, the stage of generating ideas is the brainstorm stage.
b. Multiple perspectives: The student is asked to elicit ideas and approaches concerning this challenge from "experts". In the engineering design process, this stage corresponds to consulting experts, books, and references.
c. Research and revise: Reference materials to help the student reach the goals of exploring the challenge and to revise their original ideas are introduced here. In the engineering design process, research and revise corresponds to the solution design and specifications.
d. Test your mettle: Formative instructional events are presented. In the engineering design process, the test your mettle stage corresponds to test and revise prototype.
e. Go public: This is a high stakes motivating component introduced to motivate the student to do well. The stage of go public corresponds to the final project and report in the engineering design process.

Challenge N: The following progressively more ambitious challenges enable the student to progressively deepen their knowledge to the topic being explored.

According to the authors, the different stages of the Legacy learning cycle focus to differing extents on student motivation, discovery, knowledge, and self-efficacy (key desirable student outcomes). Even though all stages of the Legacy learning cycle have a combination of them, there is usually one or two that dominate in each stage. For example, while the stages of "challenge", "generate ideas", and "go public" may all contain a significant dose of discovery, knowledge, and self-efficacy, these stages predominantly focus on student motivation. Figure 1 presents the Legacy learning cycle, the relationship between the cycle and the engineering design process, and the proposed scales for levels of student motivation, discovery, knowledge and self-efficacy. In the proposed scale shown in the figure, the arrow ends indicate maximum concentration of the specific key desirable student outcome. Even though moving away from the arrow end indicates less concentration of a key desirable student outcome, the opposite end does not indicate the absence of it. According to the authors, while high levels of student motivation, discovery, knowledge, and self-efficacy are ideally desired to maximize student learning, significant and cost-effective results may be obtained by designing challenges based on the Legacy cycle but focusing on only one or a few key desirable student outcomes depending on the student needs and/or course goals.

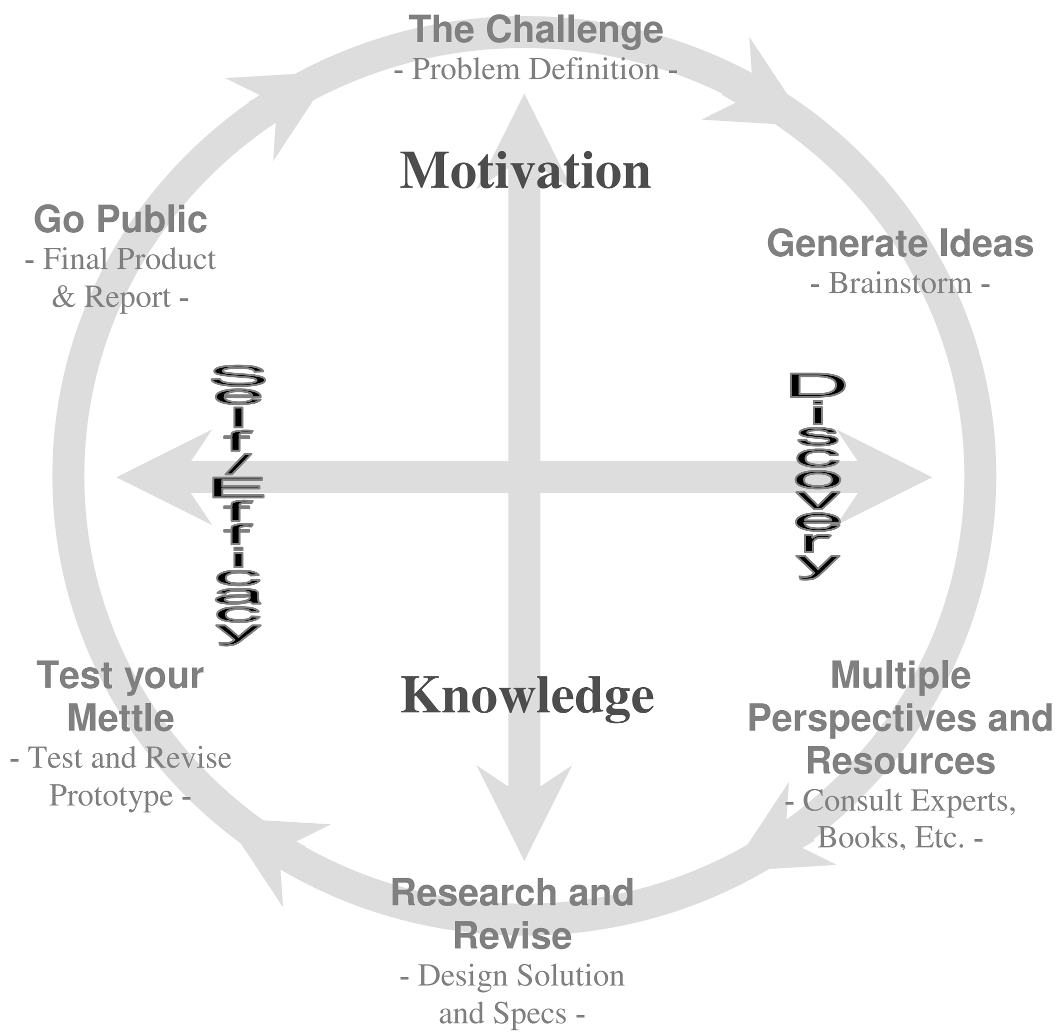


Figure 1. Relationship Between the Stages of the STAR Legacy Learning Cycle and Student Motivation, Discovery, Knowledge, and Self-Efficacy

The authors decided to initially focus on developing student challenges that will highly motivate students. In the past, the authors have had significant success in providing freshman students with challenges that have placed a significant focus on motivation. The authors' previous experiences include a challenge to design a virtual house in a 3-D virtual world[9] in Engineering Graphics and the challenge to design a spaghetti bridge in Introduction to Engineering where most students became heavily engaged and in many cases exceeded the authors' expectations. The fact that motivation plays a significant role in the learning process is not a new idea. Almost all behavioral and cognitive learning theories address the issue of motivation. Attribution theory details the importance on motivation of repeated success in the educational process through significant challenges, feedback, reflection, and change. Although there are many factors that may affect student motivation, there are common elements of motivation that affect a broad cross section of the student population where connections are made between the educational process and career goals or values. This is not to suggest that motivation is or should be the central focus of learning theories or the design of a comprehensive educational plan. However, motivation must be considered and will have significant impact on the educational process.

Academically motivating a group of students, however, can be a difficult task[5]. Creating an environment that produces motivated students is a complex process due to its individualistic nature. The difficulties include the incorporation of motivating strategies by the faculty that are effective for most members of the student population, and aligned with student, faculty, and employer's beliefs concerning what constitutes the desired goals. Rather than addressing these challenges, most programs/courses rely on simple motivational strategies and assessment metrics that have limited success. The single motivating force is often the instructor's numerical evaluation of student performance on written exams, reports, or presentations. "Teaching and testing for the right answers" is an often-used phrase that describes this situation[5]. The disconnect between the significant needs of the student and the typical simplistic motivation provided in the educational process has a negative impact on the learning environment. This disconnect may be even more severe in underrepresented populations, that include female and minority students, and among first generation college students. Research shows that motivation during the first college year is particularly important in the case of the authors' university's demographic of underrepresented and first generation students whose social/cultural environments often provide little encouragement or opportunity for tinkering[5]. Thus, motivating and confidence-building challenges for students, that start in the lower division whetting their appetites for an engineering career and that continue throughout the curriculum, will significantly impact the quality of education for all students including underrepresented and first generation students.

Human Bone Solid Mechanics Challenges

The objectives of the challenges include reinforcing students' understanding about solid mechanics and the difference between analytical and numerical solutions, and fostering students' interest in the finite element stress analysis for design and research. To reinforce solid mechanics concepts and to illustrate the mentioned relationship, the authors are developing a series of challenges that use web-based games and the involvement of students in the game design process, combined loading bone problems and the involvement of students in learning through teaching, and the concept of functionally graded material structures and their potential applications and the challenges faced in the analysis of graded materials with complex geometries. Initially, the authors' focus in the development of solid mechanics challenges has been student motivation. The theme of human bones was selected because they are attractive functionally graded material structures that can be treated with a low or a high level of complexity and because of the interaction with VANTH. The proposed motivational approach in the human bone solid mechanics challenges is based on reconnecting with students' interests, values, goals, and aspirations as discussed in the text describing each challenge. Ongoing and future work includes the strengthening of different elements of the challenges including the incorporation of more perspective and resources and additional student formative assessment. The three current human bone solid mechanics challenges are discussed in this section. In the typical VaNTH learning module it is the challenge itself that is considered and designed to be the primary motivating factor. Here we take the view that the planned learning activities themselves can be designed to be the primary motivating factor for the challenge. Ideally, both the challenge itself as well as the activities should provide motivation.

Challenge 1 Theme: Web-Based Games and the Involvement of Students in the Game Design Process- **Reconnecting with Student Interests and Values**

Look ahead

One significant interest common among many engineering students is computer games. A significant number of students that play computer games are also interested in getting involved in their design for different reasons including faculty and peer recognition and the satisfaction of contributing to the learning community. Thus, web based games may not only provide opportunities to create environments that motivate students to think reflectively about mechanics of materials content and to invest energy and time in mastering its concepts, but an opportunity to involve students in the game design process and to include student ideas that will further benefit the learning environment. Educational games that tap the student's interest and current knowledge motivate them to make connections between engineering applications and what they already know in other contexts. This non-threatening interactive environment is ideally suited for reviewing, testing, and exploring ideas and correcting misconceptions.

The overall goals of this challenge are:

- To reinforce important solid mechanics concepts
- To motivate students to take ownership of their education
- To reinforce student abilities to work in teams and communicate technical information
- To reinforce student ability to extract useful information and data from public sources

Challenge statement: Can you design the best web-based game to review an important solid mechanics concept?

a. Generate ideas: Initially students are asked to go through different games (puzzles) developed by previous undergraduate students and review important solid mechanics concepts. After students get familiar with the games, the challenge of designing a new game or a level of an existing game is given to groups of students.

b. Multiple perspectives: At this point, students have opportunities to obtain information from internal and external resources about the relevance of their proposed game and typical game platforms (work in progress).

c. Research and Revise: Reference materials to help the student revise their original ideas are introduced here[6]. In the case of existing games (e.g. bone shear and bending moment diagrams), students were provided with the basic platform for the game but created their own shear and moment diagrams along with the logic for the solution. An instructional page on the creation of the necessary elements for a game level was also posted on the website. The page includes two instructional movies that show the student how to create the images. In the case of new games, students look into a teaching toolbox developed by the authors to determine if existing games and puzzles may be modified to provide a new learning experience.

d. Test your mettle and Go public: Student games are posted in the website for faculty and student review and criticism and the best games are selected to become permanent review material. For more information, please refer to Crown and Fuentes[6]. The Bone stress concentration game and the bone optimum geometry were created by undergraduate students but do not have as many levels as the bone shear and bending moment diagram game that has been in use for a longer period of time.

Figure 1 shows some of the games currently available to students. One of the games developed involves the manipulation of forces and couples on a beam given shear and moment diagrams (see Figure 2). The concept for the first game arose out the need for students have a better understanding of shear and moment diagrams. Understanding and remembering the sign convention, effect of distributed loads, and significance of discontinuities and shape of the curves can be difficult for students. The objective of the game was to give students an open environment with immediate feedback where they could be tested on relating beam loading to shear and moment diagrams for a variety of problems from simple to complex. The goal was to create an engaging tool that was not only an assessment tool but a learning tool. To accomplish this, numerous levels of complexity would be needed such that the first levels could be easily solved by trial and error. Learning from the solution the student would then need to apply that understanding in the next level. By the end of some 20 levels, students should be able to determine complex loading from the shear and moment diagrams. The top levels should be challenging even to the professor. Some of the games have help links and tutorial movies to review the material that serve as formative assessment (see Figure 3).

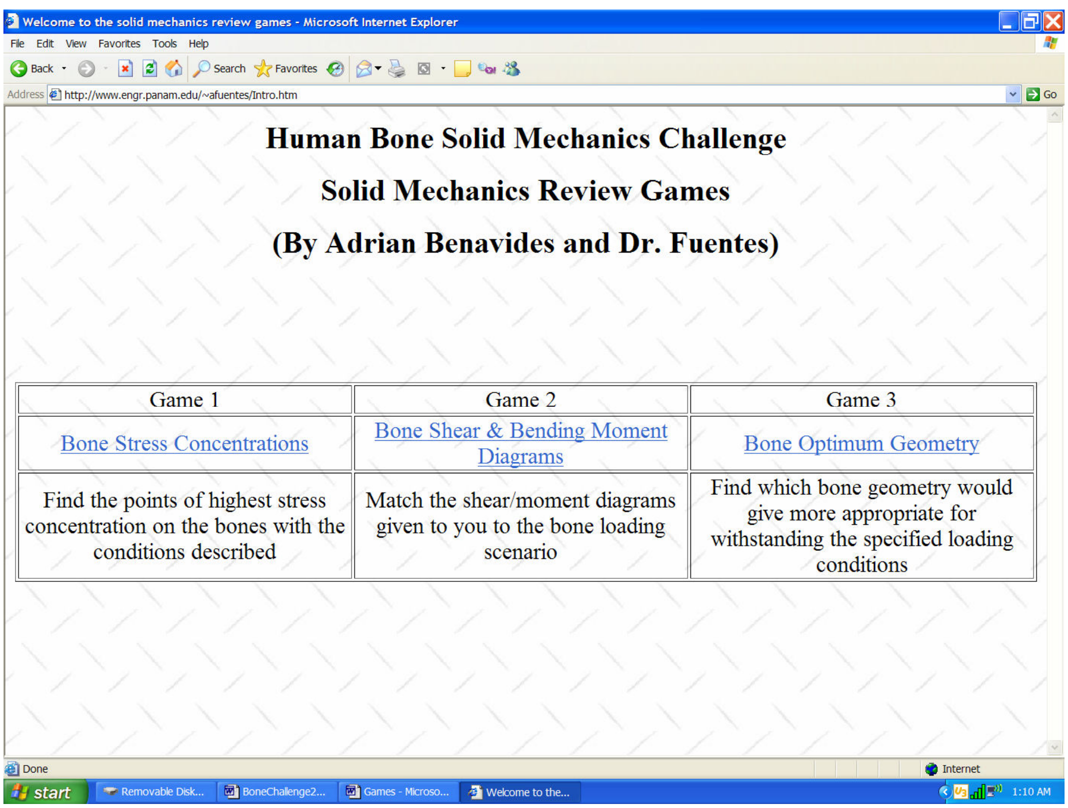


Figure 1. Human Bone Solid Mechanics Review Games

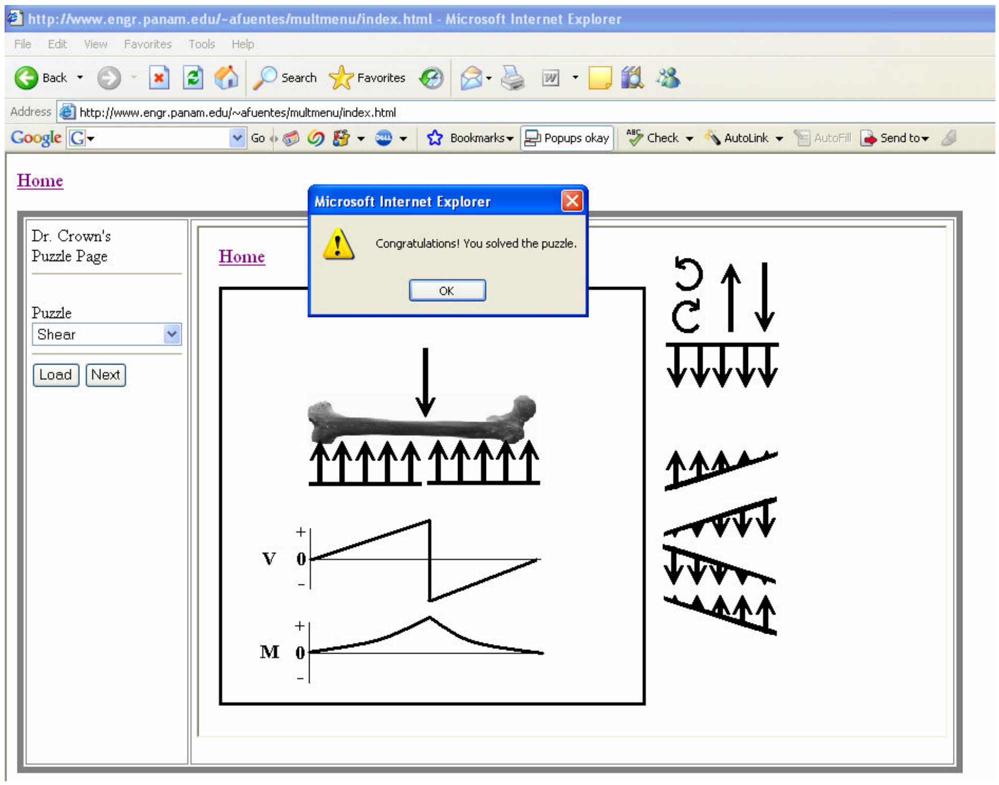


Figure 2. Shear and Bending Moment Diagram Games

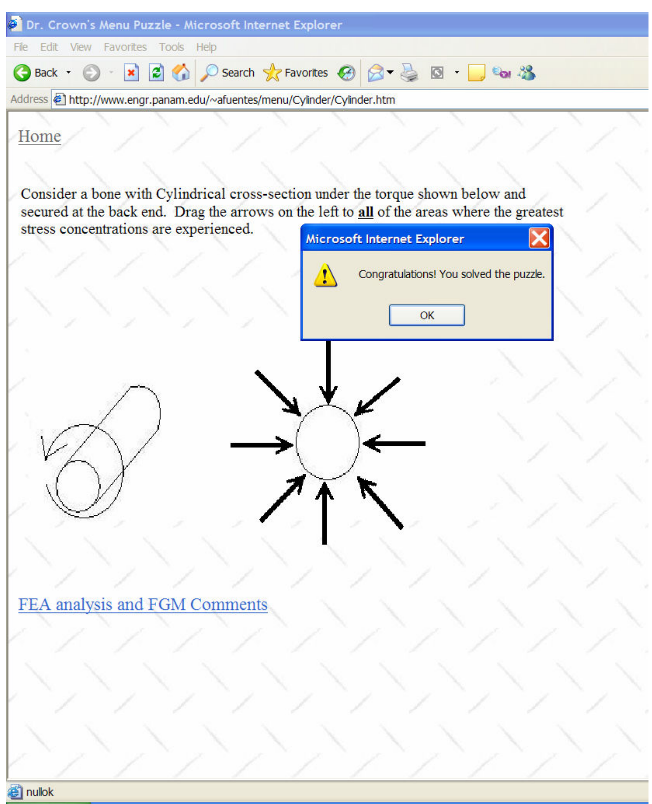


Figure 3. Bone Stress Concentration Game with Help/More Information Links

Challenge 2 Theme: Combined Loading Bone Problems and the Involvement of Students in Learning Through Teaching – **Reconnecting with Student Values and Goals**

Look ahead
The second solid mechanics challenge motivates student learning by providing a connection between their values, goals, and their developing knowledge and skills. The integration of student involvement that crosses typical boundaries in the educational setting affords unique benefits both to the learning process and to the development of the practicing engineer. A student's desire to consider and value the opinion of their peers, to share their new found knowledge with others, and to use their knowledge in a productive manner in society are built on the student's values. Providing motivation for learning that addresses the student's values may have a profound impact on the educational process as few outlets for the expression of their values exist in the current educational environment. Furthermore, students are motivated to learn when they understand the connections between the subject matter and their educational goals and that long term success may depend upon their ability to access and apply what they have learned.

The overall goals of this challenge are:

- To reinforce stress analysis of structures under combined loading (this important topic serves as a review of stress analysis theory and provides an excellent opportunity for students to develop a thorough understanding)
- To reinforce student abilities to work in teams and communicate technical information
- To reinforce student ability to extract useful information and data from public sources
- To motivate students to take ownership of their education

Challenge statement: Can you design the most irresistible review combined loading human bone problem?
a. Generate ideas: In the second challenge, after reviewing sample problems on the topic of combined loading created by former students, groups of two students are tasked to create an interesting combined loading human bone problem and solve it. The students usually brainstorm about situations where humans have bones with combined loading scenarios.
b. Multiple perspectives: At this point, students have opportunities to obtain information from internal and external resources about the relevance of their proposed project (work in progress).
c. Research and Revise: Reference materials to help the student revise their original ideas are introduced here. Previous problems also serve as a guide into how to model the bone and reasonable boundary and loading conditions. Furthermore, they are given resources to find information about human bone modeling and properties.
d. Test your mettle and Go public: Student problems are posted in the website for faculty and student review and criticism and the best problems are selected to become permanent review material.

Figure 3 shows one of the problems developed by students. The best problems are then used by all students and future generations to practice and review combined loading concepts. For information about the authors' student learning through teaching activities in other courses and the use of public forums please refer to Crown and Fuentes[7,8].

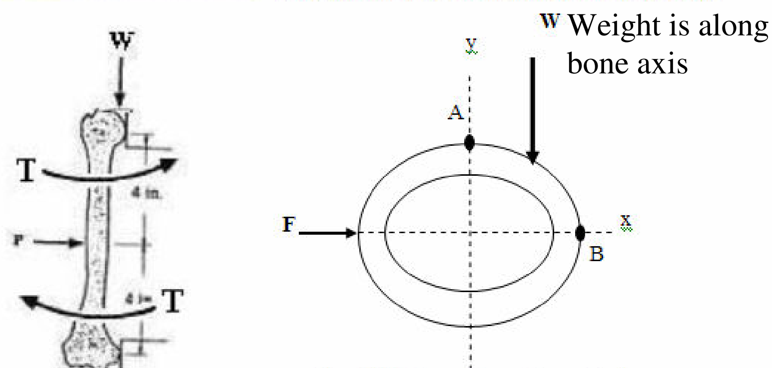
Note: Combined loading is a topic in the solid mechanics curriculum that is usually introduced after introducing topics such as stress, strain, axial load, torsional load, bending, and transverse shear. Challenge 2 supports one of the most challenging student learning outcomes in the solid mechanics course and is the foundation for Challenge 3. The student outcome supported includes the understanding that real structures are subjected to axial forces, shear forces, bending moments, and/or torsional moments simultaneously and that the resultant stress distribution is caused by all the loads. In order to concentrate on the student learning outcome, students are advised to make simplifications about bone geometry and material properties in their challenge bone problem. Thus, most student generated problems are solved with significant simplifications after reviewing the real bone geometry and material properties (e.g. assume that the material is homogeneous and behaves in a linear elastic manner). Students are asked to start thinking about how to handle structures with graded materials and complex geometry, loading, and boundary conditions. These questions constitute the foundation of Challenge #3.

Human Bone Solid Mechanics Challenge: Functionally Graded Material Structure with Complex Geometry and Loading

Challenge Bone Problem 1

(By Albert Marin)

A professional NFL lineman for the Dallas Cowboys is impacted at his thigh approximately in the middle of his femur bone with a force F = 120 lbs. At the moment of impact the femur bone was carrying most of the football player's weight (295 lbs) as shown below. Furthermore, the femur bone was being subjected to a torque of T = 100 lbft. The middle section of the FGM femur bone can be modeled as a tube having the inner diameter of 0.375 in. and an outer diameter of 1.25in. having an average elastic modulus, E_{avg} = 62.5 ksi (obtained from averaging the properties in the cross-section via integration).



Simplified Femur Bone Cross-Section

a. Determine the stress components acting on the femur at point A and B in the cross-section of impact, and show the results on volume elements loaded at those points. Assume that the weight is applied on a point at the outer radius at 45 degrees from the x- or y-axis.

Hint: the weight must be moved to the centroid of the cross section and it is necessary to add the respective couple moments.

b. Determine the maximum force of impact, F, which can be applied to the femur bone (without causing failure) under the described combined loading scenario (assume that σ_{max} = 1.25 ksi).

Figure 3. Human Bone Combined Loading Problem Created by Student

Challenge 3 Theme: What are Functionally Graded Material Structures and How to Take Advantage of Them?, Challenges Faced in the Analysis of Graded Materials and Complex Geometries – **Reconnecting with Student Aspirations**

Look ahead
Students are motivated to learn when they understand the connections between the subject matter and their career *aspirations* and that long term success may depend upon their ability to access and apply what they have learned. Students are always interested in knowledge and skills that will help them secure an interview or a job. Bringing the latest advances and research into the classroom could not only better prepare students to become innovators but motivate them to learn the fundamentals in their field of study.

The overall goals of this challenge are:

- To illustrate the relationship between classical mechanics of solids and finite element stress analysis
- To reinforce the understanding of the need for life long learning
- To reinforce student abilities to work in teams and communicate technical information
- To reinforce student ability to extract useful information and data from public sources
- To motivate students to take ownership of their education
- To integrates course content across discipline boundaries to help students build connections between related concepts and better understand the interplay between seemingly unrelated concepts

Challenge Statement: Can you find the most exciting application for FGMs? Can you estimate the stress and deformation in your femur bone?
a. Generate ideas: In the first part of the challenge 3, students have a presentation about human bones as functionally graded material structure with complex geometry and loading. After the presentation, the students are expected to be able to, among other things, define the concept of functionally graded material and describe the mechanical properties of human bone, draw appropriate free-body-diagrams of human bone in different loading scenarios, and create simplified material models of femur bones. Figure 4 shows a slide of presentation about human bones as a functionally graded material structure with complex geometry and loading. In this first part of the challenge, groups of students are asked to do research about the advantages and an exciting real-application of functionally graded material structures. The same groups of students are required to model a healthy or unhealthy human femur bone (including osteoporosis conditions) subjected to axial forces, bending moments, or torsional moments and compare their maximum stress and deformation estimates with different bone models solutions obtained through finite element analysis. The given human femur bone is a graded material structure that has elastic properties that are function of radius and the axial position. Students start by determining average properties for cross-sections and the review fundamental equations to estimate the elastic deformation and maximum stresses.
b. Multiple perspectives: At this point, students have opportunities to obtain information from internal and external resources about the relevance of their proposed solution (work in progress).
c. Research and Revise: Reference materials to help the student revise their original ideas are introduced here. Resources include presentation with analytical and FEA analysis of bones with complex geometries. Figure 5 shows a slide of presentation that illustrates different bone models used in finite element analysis. Previous problems also serve as a guide into how to model the

bone and reasonable boundary and loading conditions. Furthermore, they are given resources to find information about human bone modeling and properties.
d. Test your mettle and Go public: Student solutions are posted in the website for faculty and student review and criticism and the best problems are selected to become permanent review material.

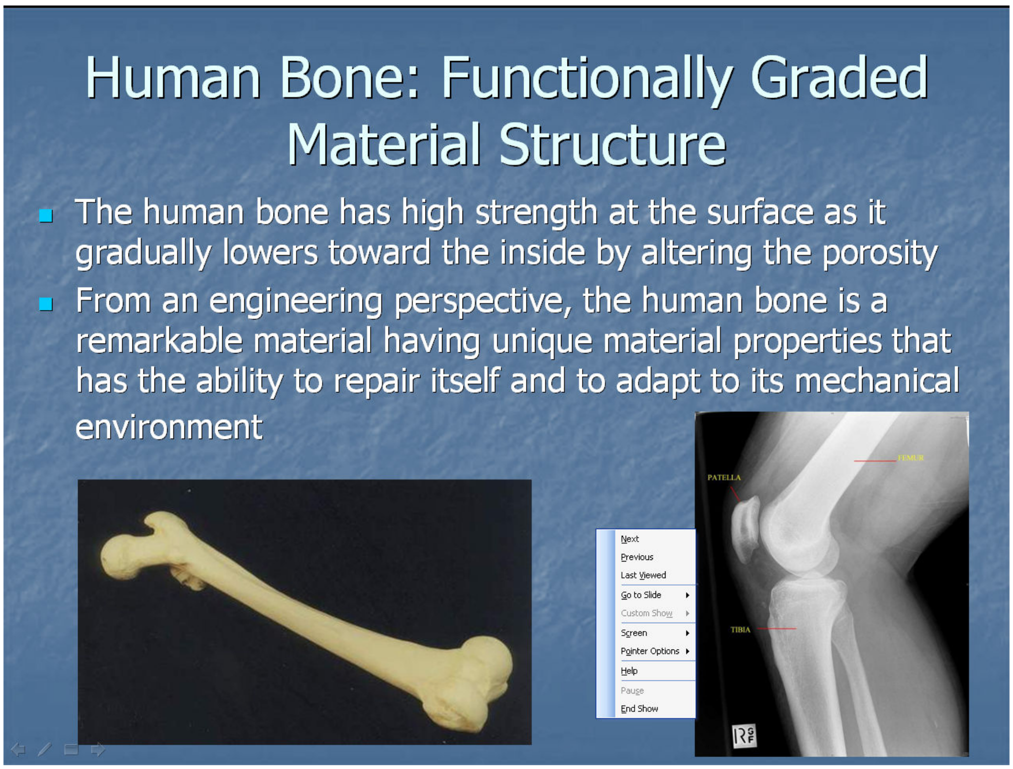


Figure 4. Presentation about Human Bones as a Functionally Graded Material Structure with Complex Geometry and Loading

Initial Impact on Student and Faculty

The solid mechanics challenges were developed in response to the identification of weaknesses in the students' fundamental understanding of concepts such as shear force and bending moment diagrams and combined loading. The challenges were designed so that they could be used by students with limited computer skills. The observed engagement of students in both solving the challenges and using the developed materials was high as compared to other class assigned projects and homework. The impact of the challenges has been positive as evidenced by performance on exams and comment on a student survey. Initial assessment indicates that students have a better competency in some of the topics covered in the challenges. The performance on a midterm exam covering the concept of Shear Force (V) and bending Moment (M) diagrams and the corresponding equations, which students used perform poorly, was almost a letter grade higher than the remaining concepts not reinforced by the challenges. Students also strongly indicated on course surveys that they believed the challenges benefited their learning.

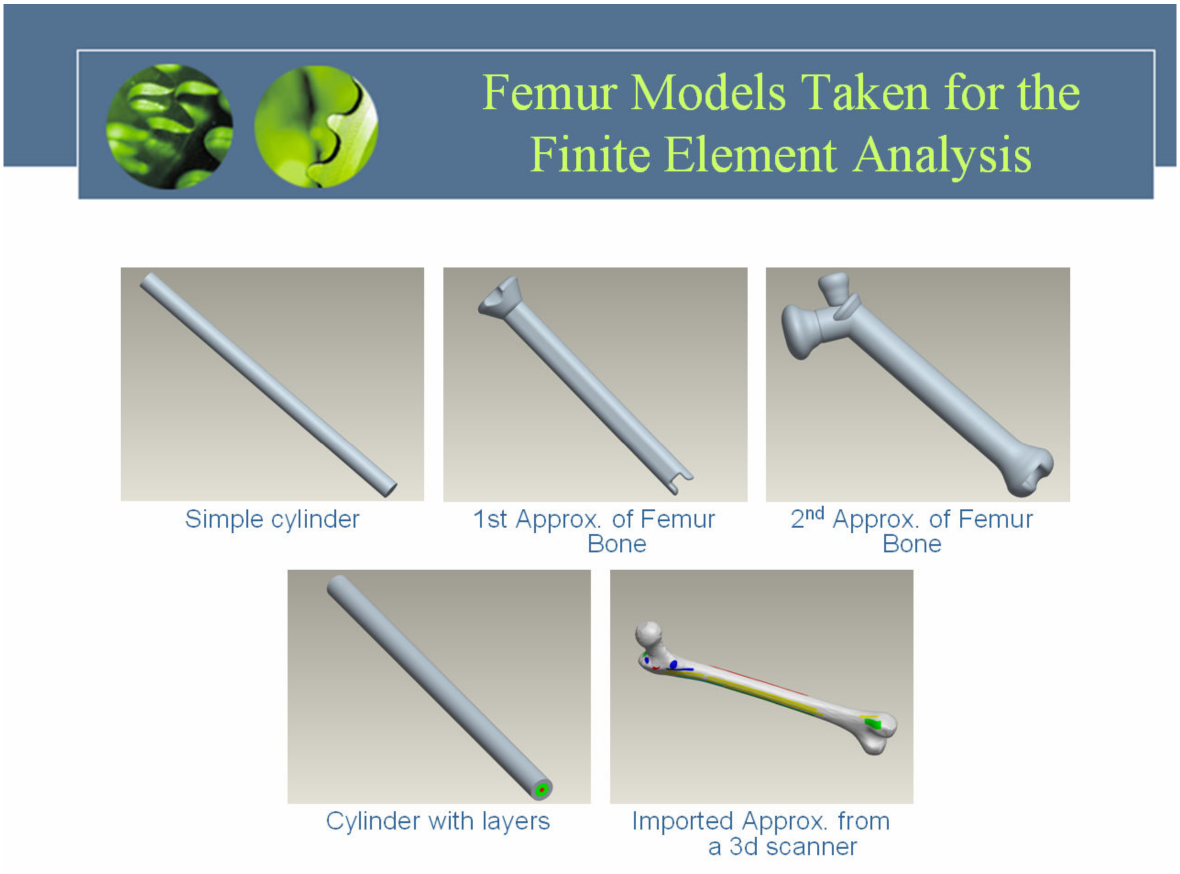


Figure 5. Bones FEA Models with Different Simplified Geometries

In the midterm student survey (n=25), 96% of the students strongly agree or agree that challenge 1 help them understand the targeted concepts. The majority of the students (~75%) strongly agree that the games developed were clear and easy to understand. The same percentage of students strongly agree or agree that they will remember for a long time everything that have learned in the Challenge 1. While almost 100% of the students recognize that they often use computers, only 70% claimed to be very skilled in using the computer. Furthermore, 92% of the students strongly agree or agree that they would like to see these teaching methods used in this class used in other classes.

In a survey (n=21) given towards the end of the semester, the students were asked their input about the challenge of creating their own problems. The first part of the survey consisted in student ranking the challenge from 1 (inadequate) to 10 (excellent). The average ranking from the class was an 8.2. The second part of the survey requested comments from the students with respect to the challenge and student learning, student academic integrity, student feedback, student motivation, and necessary modifications. The most illustrative comments are given below:

- "I think if a student can come up with an original problem, then he definitely knows the content."

- "The student gets to see work from other students' perspective. A huge data bank of problems with solutions would be beneficial since it allows the student to go and supplement their knowledge by practicing with some of the problems. Also is beneficial to the students that want to refresh their memory after having taken the course in the past"
- "Great idea! I think it is a well thought up idea and it will be very beneficial to students"
- "This is a very good idea to encourage academic integrity and motivation. Creation of their own problem that their peers will eventually see motivates students to put effort into the problem they create"
- "It actually does help the student learn the subject at a different level"
- "Great tool for exams"
- "It (the challenge) promotes an indirect form of group learning and responsibility"
- "Good idea. It will be helpful if everybody used the same format."
- "It was new and a positive experience"
- "Some were GOOD, while others just go basic. It will get better"

The cost of development of instructional materials that provide an effective learning environment is often high. The challenges provided a mechanism for assigning students the task of creating instructional content outside the classroom and benefited from their involvement in the process. The solution to the challenges developed by students (games or course materials) benefited the students designing them, the students playing or using them, and the faculty members interested in improving conceptual learning and in increasing course content and/or materials. Some class time was allocated for the discussion of the challenges. Total class time invested was approximately one class period (50 minutes). However, the student time invested was significant higher that the total intended time of 6 to 8 hrs. Final challenge was trimmed to reduce the burden on the students. Current work includes minor modifications, mainly on Challenge 3, and further assessment.

The solid mechanics challenges created a knowledge centered, community centered, learner centered, and assessment. The challenges provided a knowledge-centered environment in that students were forced to organize and present their findings in a form that others could understand. The challenges also maintained a limited separation between acquiring new knowledge and applying that knowledge. The involvement allowed the authors to capitalize on the expertise and perspectives of students and to create a sense of collaboration among students and promote a sense of community. The challenges provided a mechanism for fostering a learner-centered environments. Students who understood new concepts often translated that understanding to other students in a different form based on an understanding of the needs of their peers. Finally, the challenges provided a mechanism for fostering an assessment-centered environment that helped to make acquisition, assimilation, and application of knowledge a concurrent process. Students were motivated to get heavily involved in the challenges by the fact that their work was being evaluated by their peers and that it has some useful purpose that will continue to serve future generations of students.

Conclusion

The impact of the challenges in the undergraduate solids mechanics course was at least threefold in terms of providing a mechanism for student learning through discovering and teaching, for fostering a student learning environment that is manageable for faculty, and for fostering a community centered environment. The receptivity of the challenges and student developed materials was extremely positive. The solid mechanics challenges provided a mechanism for fostering learner-centered, knowledge-centered, community-centered, and assessment-centered learning environments. Furthermore, the challenges integrate course content across discipline boundaries and help students build connections between related and seemingly unrelated concepts. The challenges demonstrate to students that their education is the process of building an integrated knowledge base that will ultimately prepare them for applying that knowledge in their career.

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