Session 3268

Continuum Mechanics as the *First* Mechanics Course

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Abstract

This paper describes an introductory course in continuum mechanics. Taught within Harvey Mudd College's broad, unspecialized curriculum, the course is designed for second-semester sophomores or juniors who have not had any of the standard engineering courses in mechanics (i.e., statics, dynamics, or strength of materials). We describe in this paper the course's development and its contents, including its many illustrative real-world case studies. We also show how it is uniquely positioned to demonstrate the connections between solid and fluid mechanics, as well as the larger mathematical issues shared by both fields, to students who have not yet taken courses in fluid mechanics and/or strength of materials. We also discuss our success in introducing continuum mechanics at such an early point in the curriculum, as we detail the course's implementation over eight semesters, its assessment during that time, and the response of some 300 students who have taken the course.

Introduction

Continuum mechanics is a course taken routinely by graduate students or, less frequently, by advanced undergraduates who are likely to go on to graduate work in mechanics. As a result of changes made within Harvey Mudd College's broad, unspecialized engineering curriculum, we have developed an introduction to continuum mechanics for second-semester sophomores or juniors who have not had any of the standard engineering courses in mechanics (i.e., statics, dynamics, or strength of materials).

The essence of continuum mechanics, the internal response of materials to external loading, is often obscured by the complex mathematics of its formulation. By building gradually from one-dimensional to two- and three-dimensional formulations, we are able to make the essence of the subject more accessible to undergraduate students. From this gradual development of ideas, with many illustrative real-world case studies interspersed, students develop both physical intuition for how solids and fluids behave, and the mathematical techniques needed to begin to describe this behavior. At the same time they gain a unique appreciation for the connections between solid and fluid mechanics.

This course is well positioned to demonstrate the connections between solid and fluid mechanics, as well as the larger mathematical issues shared by both fields, to students who have not yet taken courses in fluid mechanics and/or strength of materials. The context and foundation provided by this course are available to students as they specialize (by choosing electives, by selecting career paths, or by going to graduate school) in either solid or fluid mechanics, or specialize in the connections themselves by returning to a deeper study of the overarching field of continuum mechanics.

Over four academic years, we have had success in introducing this subject at such an early point in the curriculum. Such a course could replace statics and first courses in strength of materials and in fluid mechanics in many curricula. We anticipate that such a course will become more common in unspecialized curricula such as ours, as well as in new curricula, and in traditional curricula, many of which feel dual pressures to become broader and to reduce the number of credit hours.

In most engineering curricula, students take a year of mechanics in their introductory physics courses. Then, in civil and mechanical engineering programs, they will more than likely take one-semester introductory courses called statics, dynamics, and strength of materials—and there is a great deal of repetition involved. Depending on one's point of view and rhetorical preferences, one might regard this aspect of curricular structure as useful reinforcement, or as repetition that consumes far too much of an increasingly scarce resource, curricular time. Indeed, one might argue—and this is certainly the stance implied by Harvey Mudd's unspecialized program[1]—that such repetitious reinforcement mistakenly substitutes topical content in the curriculum for a more holistic emphasis on engineering as a process that may be better learned by applying the principles of and approaches to engineering modeling and problem solving across a broader range of topics. There is certainly an attendant risk of making topical coverage too superficial, but there is perhaps an equally great risk of obscuring the power and generality of a process-based approach by too much repetition of the same topic(s) in ever greater detail.

In our later discussion of student reaction to this course, we will also note that students were engaged by our devoting a significant portion of the course to a series of case studies. This approach, too, bears something of the "cost" of substituting meaningful discussions of both technical and social aspects of events such as the 1981 collapse of the Kansas City Hyatt Regency Hotel and the construction of the Three Gorges Dam in central China for further "depth" in the analysis of one-dimensional bars or of the hydrostatics of dams. It seemed to us that such case studies would offer conceptual reinforcement, real-world application, and an extension and expansion of course material whose benefits far outweighed this cost. Indeed, students have responded very well to the case studies: their interests have been piqued by real-world aspects of engineering, and they have been inspired to delve further into the underlying technical issues.

1st Year	F	S
Chemistry I, II	4	4
Mathematics I, II	4	3
Physics I, II	2	4
Hum. & Soc. Sci. I, II	4	3
Intro. Engrng. Design		3
Computer Science	3	

2nd Year	F	S
Mathematics III, IV	3	3
Physics III	4	
Hum. & Soc. Sci. III, IV	3	3
Biology or Free Elective	3	3
Intro. Engrng. Systems	3	
Experimental. Engrng.		3
Design Rep. & Real.		1
Continuum Mechanics		3
CREDITS (1st, 2nd yrs.)	66	

3rd Year	F	S
Chem. & Thermal Processes	3	
Electron. & Magnet. Devices	2	
Computer Engrng.		3
Adv. Engrng. Systems I, II	3	3
Engrng. Seminar I, II	0	0
Engrng. Clinic I		3
Technical Elective I		3
Hum. & Soc. Sci. V, VI, VII	6	3

4th Year	F	S
Materials Engrng.	3	
Engrng. Seminar III, IV	0	0
Engrng. Clinic II, III	3	3
Technical Elective II, III	3	3
Hum. & Soc. Sci. VIII–XII	6	9
Integrative Experience	3	
CREDITS (3rd, 4th yrs.)	62	

Figure 1. The Harvey Mudd College B. S. E. curriculum (2003–05 Catalogue).

The paper will describe the course content; it will also address the factors that led to its development, and how effectively the resulting course has addressed those factors. Details of the course's implementation over eight semesters, its assessment during that time, and the response of some 300 students are discussed.

The Harvey Mudd Context for Introducing Mechanics

Harvey Mudd College was founded in 1955 as a "liberal arts college of engineering and science" with a mission to "educate engineers . . . so that they may assume leadership in their fields . . ." The College's Engineering program was gifted with "Founding Fathers" who took a decidedly unusual approach to fulfilling the aims of the Grinter report[2]. They established an Engineering program that built a sound theoretical base that was then strongly coupled to the realism of engineering practice. Engineering's Founding Fathers developed the Harvey Mudd Clinic program—Harvey Mudd's three-semester capstone experience—to bring professional practice to on-campus students. Subsequent colleagues developed (and evangelized) the first-year design course (E4) that exposes students to client-based design work as the cornerstone of its Engineering program. A current overview of the history and philosophy of the Mudd Engineering program is found elsewhere[1], while details of the current curriculum are shown in Figure 1.

The Harvey Mudd College Engineering curriculum has three "stems"[3]: *engineering science*, with a focus on introductions to mechanics, thermodynamics, materials science, and electrical and computer engineering; *systems engineering*, a sequence of three courses that focus on modeling and analyzing lumped-element models of physical systems; and *design*, including (1) a freshman design course[4, 5], (2) sophomore courses requiring students to design and make real tools, such as a hammer and a screwdriver, and to perform experiments to find detailed design parameters, and (3) Engineering Clinic projects in the junior and senior years[6–8]. HMC's engineering program is unified by the themes that *design* is the central activity of engineering[9]; that engineers typically design *systems*; and that such design requires good *models* of the physical systems[10].

Design, clearly an integral part of HMC's curriculum, "peaks" in Clinic in the junior (3 cr.) and senior (6 cr.) years[6–8]. Since Clinic projects often require deep domain knowledge, it is reasonable to ask whether students can carry out in-depth design and development after a broad, general program. Our students can and do, as is evidenced by the willingness of companies to pay substantial fees for their HMC Clinic projects. In fact, students do first-rate design (and supporting analysis) because they know the fundamentals of the relevant discipline(s) and how to formulate and solve a technical problem. The Clinic project motivates them to acquire the needed domain depth. The Clinic setting focuses students' attention, and they work as they would in industry—on new and unfamiliar problems wherein they have to acquire and use new knowledge.

Clinic and E4 problems are inherently multidisciplinary, or more accurately *cross-disciplinary*. The HMC curriculum, with its breadth and depth, and its emphasis on the process and tools common across disciplinary boundaries, prepares students to address such problems.

Thus, in sum, the HMC program couples a *broad* education in engineering fundamentals to a consistent exposure to design—from conceptual design and design methods in the first year through client-oriented, detail-design experiences in the last two. Design is the integrator of our broad undergraduate program. We have ample anecdotal and survey data from:

- *alumni*, that these experiences provide a framework for "lifelong learning," and
- *graduate school faculty*, that our graduates make excellent, unusually independent, and well-grounded graduate students, and
- *employers*, that HMC alumni "hit the deck running" when they assume their first positions in industry.

In order to maintain this focus on both process and interdisciplinary connections, while simultaneously providing sufficient depth to our graduates, we must think of our curriculum in terms of being able to produce graduates who are exceptionally competent, who "think like engineers" using standard processes, and who adapt easily to new technical challenges. When designing our curriculum, we are concerned with what an exceptionally competent engineer ought to know about a range of disciplines and methods. Due to our unspecialized major, students take only one required introductory course that addresses "mechanics" or mechanical engineering. For many years, this one course consisted of half-courses in dynamics and in strength of materials that were joined in a one-semester "mechanics" course, which meant a significant overlap with required physics coursework and repetition of concepts. In 1999–2000, during a comprehensive internal review of our curriculum, we realized that our department goals might be better served if this course included more new material, and taught skills that could be extended—for example, from solid to fluid mechanics. An exceptionally competent engineer, we agreed, ought to be conversant with the fundamentals of fluid mechanics. (Although upper-division electives in fluid mechanics and compressible flow are available, they are not part of the required engineering core.) One of the changes made as a result of this curriculum review was the overhaul of our introductory mechanics course. We hoped that we would provide our graduates with needed knowledge by including fluid mechanics in the course, and that by demonstrating the continuum mechanics approach to both solid and fluid mechanics we would teach our students a useful and elegant process.

Contents of the Continuum Mechanics Course

The course demonstrates the connections between solid and fluid mechanics, and the larger mathematical issues shared by both fields, to students have not yet taken courses in fluid mechanics and/or strength of materials. The context and foundation provided by this course are available to students as they specialize (by choosing electives, by selecting career paths, or by going to graduate school) in either solid or fluid mechanics, or specialize in the connections themselves by returning to a deeper study of this overarching field of continuum mechanics. As more is learned about the details of each sub-field, the subject of continuum mechanics grows richer.

The essence of continuum mechanics, the internal response of materials to external loading, is often obscured by the complex mathematics of its formulation. By building gradually from one-dimensional to three-dimensional formulations, this course makes the essence of the subject more accessible to undergraduate students. Students develop both physical intuition for how solids and fluids behave, and the mathematics necessary to describe this behavior. At the same time they gain a unique appreciation for the connections between solid and fluid mechanics.

We take a consistent continuum approach to considering the responses of solids and fluids to external loading: by repeatedly emphasizing the idea that complete continuum models account for: the kinematics of deformation; the intensity of internal forces, or stress; constitutive laws that relate stress to deformation; and Newton's second law. We develop these four fundamental concepts in one dimension, and then apply them to the axially-loaded bar. (We also introduce indeterminate structures here.) We follow by delineating the four fundamental concepts in two and three dimensions, and we then introduce the stress and strain tensors in Cartesian coordinates. We go on to apply the concepts to torsional loading and to pressure vessels, and we make good use of the equations of stress transformation and Mohr's circle to develop more complete descriptions of their stress states. We then discuss beam theory and column buckling, again making clear that the four elements of continuum mechanics modeling. In the last third of the course, we extend this modeling to fluids, once again considering the kinematics of deformation, stress, constitutive laws that related stress to deformation rate, and Newton's second law. We discuss the similarities and differences between solids and fluids, and the assumptions under which our theories are valid.

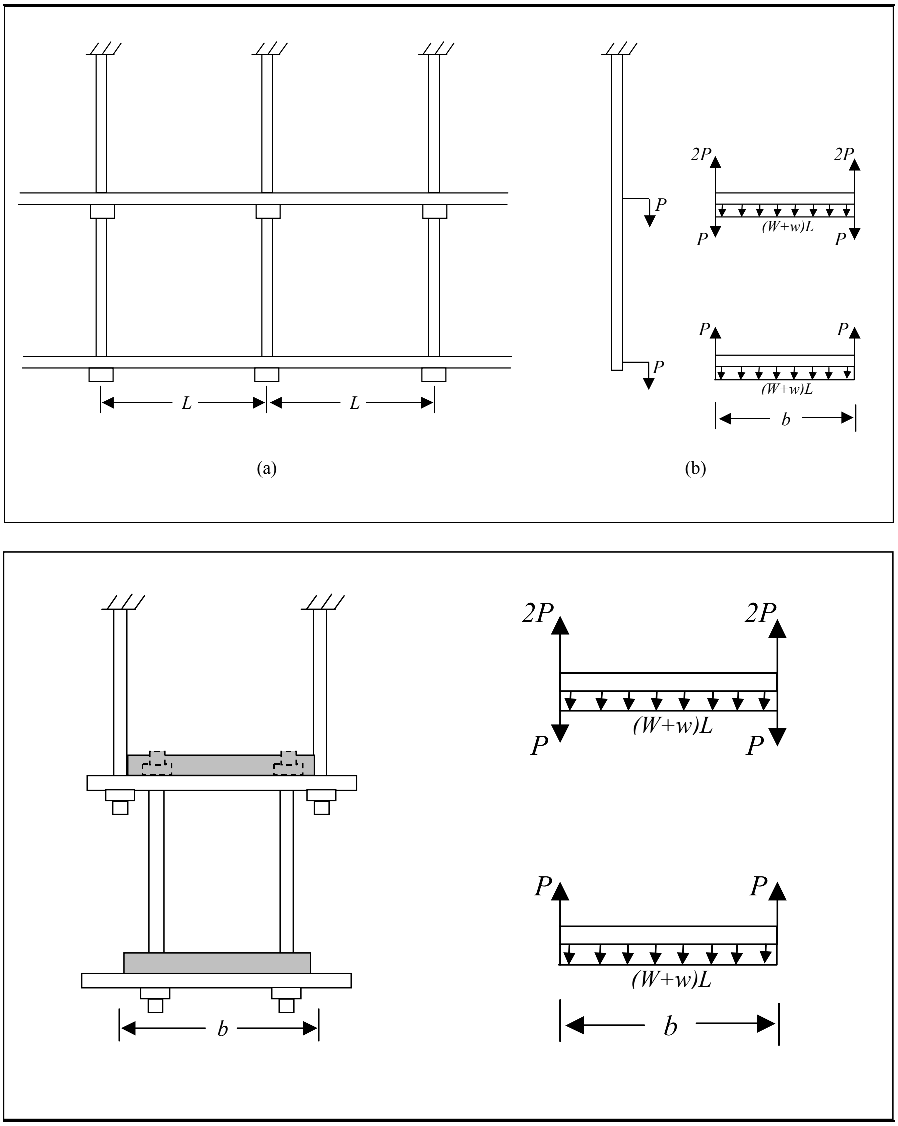


Figure 2. *Top*: (a) An elevation of the Hyatt Regency 2nd and 4th floor walkways as originally designed. (b) An end view and free-body diagrams of the support beams. *Bottom*: Extending the model of the walkways and their supports to reflect the redesign. An end view of the 2nd and 4th floor walkways designed so that the 2nd floor walkway hangs from the 4th floor supporting beams, and free-body diagrams of a typical pair of supports. Note that the forces supported by the hanger rods are unchanged from the original design.

Several case studies are introduced to demonstrate real-world examples of the types of loading, geometry and behavior discussed in each chapter. The case studies are intended to show how the material learned in that chapter can be applied to perform mechanical and forensic analyses of real engineering problems. We will not oversimplify these real problems, but will present and discuss their complexities and show that a particular element, say, "torsional failure," or "buckling," is only one aspect of a larger situation. This helps students develop a physical understanding of mechanics, and of the consequences of "the internal response of materials to external loading." Such real-world applications of the theory are essential to a course that truly addresses continuum mechanics for an undergraduate audience. For example, the case study on the Hyatt Regency walkway failure encourages students to apply recently-gained knowledge to perform their own analyses of the system as designed and as built (Figure 2). The case study on the St. Francis Dam (see Appendix) allows students to apply their knowledge of hydrostatics, and also encourages them to make connections, seeing the dam as a beam under distributed loading.

A topical outline of the course includes the following subjects. This outline closely tracks a manuscript of specially-prepared notes[11], the only required text for the course, aimed at undergraduates being introduced to solid and fluid mechanics, rather than the more advanced intended audience for other continuum mechanics texts[12-14].

- **Introduction** (Motivating Example: Remodeling an Underwater Structure; Newton's Laws: First Principles of Mechanics; Equilibrium; Definition of a Continuum; Mathematical Basics: Scalars and Vectors).
- **Strain and Stress in One Dimension** (Kinematics: Strain; The Method of Sections and Stress; Stress-Strain Relationships; Equilibrium; Stress in Axially Loaded Bars; Deformation of Axially Loaded Bars; Equilibrium of an Axially Loaded Bar; Indeterminate Bars; Thermal Effects; Saint-Venant's Principle and Stress Concentrations; Strain Energy in One Dimension; A Road Map for Strength of Materials)
- **Case Study 1**: Collapse of Kansas City Hyatt Regency Walkways
- **Strain and Stress in Higher Dimensions** (Poisson's Ratio; The Strain Tensor; Strain as "Relative Displacement"; The Stress Tensor; Generalized Hooke's Law; Limiting Behavior; Properties of Engineering Materials; Equilibrium; Formulating Two-Dimensional Elasticity Problems)
- **Applying Strain and Stress in Higher Dimensions** (Torsion; Pressure Vessels; Transformation of Stress and Strain; Failure Prediction Criteria)
- **Case Study 2**: Pressure Vessels
- **Beams** (Calculation of Reactions; Method of Sections: Axial Force, Shear, Bending Moment; Shear and Bending Moment Diagrams; Integration Methods for Shear and Bending Moment; Normal Stresses in Beams; Shear Stresses in Beams)
- **Case Study 3**: Physiological Levers and Repairs
- **Beam Deflections** (Governing Equation; Boundary Conditions; Solution of Deflection Equation by Integration; Moment-Area Method; Beams with Elastic Supports; Strain Energy for Bent Beams; Flexibility Revisited, and Maxwell-Betti Theorem)
- **Instability: Column Buckling** (Euler's Formula; Effect of Eccentricity)
- **Case Study 4**: Hartford Civic Arena
- **Connecting Solid and Fluid Mechanics** (Pressure; Viscosity; Surface Tension; Governing Laws; Motion and Deformation of Fluids (including vorticity and constitutive equation for Newtonian fluids))
- **Fluid Statics** (Local Pressure; Force Due to Pressure; Fluids at Rest; Forces on Submerged Surfaces)

- **Case Study 5**: St. Francis Dam
- **Fluid Dynamics: Governing Equations** (Description of Fluid Motion; Equations of Fluid Motion; Integral Equations of Motion; Differential Equations of Motion; Bernoulli Equation)
- **Fluid Dynamics: Applications** (How Do We Classify Fluid Flows?; What's Going on Inside Pipes?; Why Can an Airplane Fly?; Why Does a Curveball Curve?)
- **Case Study 6**: Blood Flow
- **Solid Dynamics: Connections** (Continuity, or Mass Conservation; $\underline{F} = m\underline{a}$, or Momentum Conservation; Constitutive Laws: Elasticity; Canonical Problems)

Assessing the Continuum Mechanics Course

Through our departmental assessment process, we have obtained both student survey- and instructor rubric-based data that indicate students are achieving the course's desired learning outcomes. Rubrics have been developed to measure to what degree students develop particular skills, for example the ability to calculate the deflection of a beam's neutral axis or the principal stress state under given loading. These skills and rubrics follow directly from the learning objectives for the course, shown in Figure 3. Sample rubrics are shown in Figure 4.

Continuum mechanics is the analysis of the internal response of continua (solids and fluids) to external forces and torques. By the end of the semester, students will be able to:

- Define and understand the concepts of stress and strain;
- Apply these concepts to a wide range of engineering problems;
- Possess sufficient physical intuition to identify the relevance of continuum mechanics to the design and analysis process;
- Interpret and apply the governing equations for the motion and equilibrium of continuous media;
- Describe and explain the similarities and differences between solid and fluid responses to loading;
- Make both qualitative and quantitative predictions about complex systems, based on the physical intuition developed in E83;
- Identify, interpret, and distinguish the assumptions and approximations made in modeling real problems; evaluate appropriateness of assumptions.
-

Figure 3. Course objectives for E83: Continuum Mechanics.

We have been gratified to note that these skills have not been diminished by the change in focus from dynamics and strength of materials to continuum mechanics. Student scores on learning outcomes such as their ability to prepare shear and bending moment diagrams, and their ability to analyze a member in torsion, have been consistently high, averaging 4.3 on a five-point scale. We note that the students have achieved desired learning outcomes in skills we would have expected them to take from a course in statics and/or strength of materials, and from a course in fluid mechanics, *and* additional skills in continuum reasoning and writing that have been developed by the unique format of this course. Our use of case studies in the course notes and in lectures has given students opportunities to consider the issues involved in real-world problems in essays and short-answer exam questions. Due to the inclusion of case studies in student reading, assignments, and exams, as well as in classroom discussions, we have also been able to evaluate learning outcomes such as oral and written communication skills and students' understanding of professional and ethical responsibility. This has been a boon both for our students and for our department in communications with ABET.

Over six semesters assessed in this way, students in the continuum mechanics course have achieved an average score of 4.3 on a 5-point scale. Unfortunately, the department initiated the use of rubric-based assessment after the continuum mechanics course was developed, so data are not available to compare these results with those for the former course. However, the department has agreed that a mean score of 4.0 on a 5-point scale is satisfactory, and we are gratified by the measured results. We have also queried—albeit informally—our colleagues who have taught related upper division electives both to students who have taken this recent course on continuum mechanics and to (earlier) students who had taken its predecessor course, which was basically a half-semester course in dynamics combined with a half-semester introduction to strength of materials. These elective courses in the Harvey Mudd curriculum include E171: Dynamics of Elastic Systems, E172: Structural Mechanics, E173: Applied Elasticity, and E176: Numerical Methods in Engineering. Our colleagues have indicated that alums of the continuum mechanics course demonstrate a better understanding of the concepts of stress, strain, and kinematics; more readily understand what finite element methods are about; and they also do better in applying beam theory and other structural models to a variety of static and dynamic applications.

Student response to the Continuum Mechanics course has been quite favorable. It suggests that in addition to achieving these specific learning outcomes, students *are* successfully making conceptual connections, and are learning the ideas and methods of continuum mechanics. In the Fall 2003 semester, students were asked to describe the most important or interesting things they learned in the course. Many students discussed the method of sections, beam theory, or Bernoulli's equation; others made comments about the "continuum" aspects of the course. Some responses follow:

> "Probably the most useful concept I gained was the overall description of solids and fluids as continua, and the corresponding ability to apply many of the same principles to each. … My knowledge of mechanics before this class was based mainly on 'inelastic collisions' style knowledge."

> "I was glad to escape from classical physics and 'billiard ball' relations to understanding the internal forces in objects using the method of sections…What specifically interested me about beam theory was the application to buildings and construction, for example the World Trade Center discussion."

> "The most important things I learned would definitely be the 'language' and 'art' of continuum mechanics. Understanding what stress and strain are led to understandings of material behavior; for example identification of the strongest and weakest regions of objects or systems. … The flexibility of the methods and formulas learned in this class to be used in a wide range of applications is really impressive and useful. The same concepts were able to be applied to structures, motors, and even the human body."

Skill #1	Formulate and solve beam deflection problems.	
Superior	5	Identifies, explains and solves the equilibrium equation(s) and boundary conditions to determine the requisite deflection(s). Dimensions are consistent and correct.
Good	4	Identifies (without explaining) and solves the equilibrium equation(s) and boundary conditions to determine the requisite deflection(s). Solution is clear and well-annotated.
OK	3	Identifies (without explaining) and solves the equilibrium equation(s) and boundary conditions to determine the requisite deflection(s). Solution is unclear or poorly organized.
Marginal	2	Identifies (without explaining) and incorrectly (math, algebra, or dimensional error) solves the equilibrium equation(s) and boundary conditions to determine the requisite deflection(s).
Inadequate	1	Incorrectly states equilibrium equation(s); incorrectly states boundary conditions; completes calculations incorrectly.

Skill #2	Apply the principle of superposition to determine beam deflections.	
Superior	5	Recognizes sub-problems that can be assembled to properly model the given problem and correctly determines the proper component deflections.
Good	4	Recognizes some/most of the sub-problems and determines appropriate (to his/her recognition) deflections of sub-components.
OK	3	Recognizes some/most of the sub-problems but makes at least one error in modeling and/or calculation of deflection.
Marginal	2	Recognizes that superposition can be applied but is unable to perform decomposition.
Inadequate	1	Does not recognize role of superposition in analyzing beam deflections.

Skill #3	Write a clear, organized report.	
Superior	5	Prepares report with logical flow, and effective introduction and closing; report feels complete.
Good	4	Makes some effort to make report flow effectively, not perfect.
OK	3	All sections are present, perhaps not in most effective order.
Marginal	2	Missing one section. No effort at transitional material.
Inadequate	1	Missing multiple sections, weak transitions; poor or missing explanations of data, equations, or schematics.

Skill #4	Explain and apply Bernoulli's equation, and justify its use.	
Superior	5	Lists *and justifies* necessary assumptions, correctly calculates pressure drop or change in fluid velocity along a known streamline.
Good	4	Lists (without justifying) assumptions, correctly calculates pressure drop or change in velocity along streamline.
OK	3	Correctly calculates pressure drop or change in velocity without stating assumptions or drawing streamline.
Marginal	2	Recognizes that Bernoulli's equation should be applied, however, does not state assumptions, and incorrectly completes calculation.
Inadequate	1	Does not recognize that Bernoulli's equation should be applied to problem.

Figure 4. Example rubrics for assessment of student learning outcomes on various assignments and exams. *Note*: with respect to Skill #3, the HMC engineering department has also developed a multidimensional writing rubric for use in evaluating student work and providing feedback.

"One of the most important things we learned was the similarities between fluids and solids. … Another aspect that I thoroughly enjoyed was the case studies. I really enjoyed the [Three Gorges] dam case study which involved environmental and social impacts, and solids and fluids."

"The idea of the tensor has expanded my view of the physical world and the way we describe it."

"The most useful things I take out of [this class] are the ways to think about problems. From considering the internal reactions of structures, to design considerations in choosing materials/dimensions, I have learned a great deal about how the world around me is planned and constructed. This is everything I hoped I would learn in this class."

Conclusions

We feel that our approach has made the complex and challenging subject of continuum mechanics accessible to students early in their studies, allowing them to develop a method of analysis that will serve them well in future endeavors. The development of continuum mechanics from straightforward definitions in one dimension to higher dimensions has allowed us to introduce sophomore-level students to second-order tensors that make sense. We have endeavored to keep the mathematics from obscuring the elegance and value of continuum mechanics, and student performance indicates that we have succeeded. By including discussions of several case studies that showcase not just the details but the multi-faceted big picture, we have demonstrated to students the utility of their course material and also shown them how this material contributes to a real-world design or failure.

Our course was developed in response to pressures to maintain our broad, unspecialized curriculum while providing sufficient depth to produce exceptionally competent graduates. The dual pressures to become broader and to reduce the number of credit hours – that is, to cover more material in less curricular time – are having an impact on many of our peers[15-16], and we have found that an early course in continuum mechanics is a reasonable and effective way to address these pressures. In addition to learning the desired material, students have responded very well to the connections between solids and fluids, and even to the tensor math involved. There has been a particularly warm reception for the case studies that demonstrate complex real–world applications of the course material.

Appendix: Case Study of the Design and Collapse of the St. Francis Dam

This case study is representative of the several case studies included in our course. These materials serve to demonstrate to students some real-world applications of the concepts they have learned, without oversimplifying, to help students understand that real-world engineering is complex, involving many issues. We also hope that these case studies raise questions involving engineering ethics and economics that feed into classroom discussions of the larger context for engineering projects. The problems following the case studies are often assigned as part of students' weekly homework.

At three minutes before midnight, March 12, 1928, the St. Francis Dam—built to supply water to the growing city of Los Angeles—collapsed. During the early morning hours of March 13th, more than 38,000 acre-feet of water surged down from 1650 feet above sea level. At its highest, the wall of water was said to be 78 feet high; by the time it hit Santa Paula, 42 miles south of the dam, the water was 25 feet deep. Almost everything in the water's path was destroyed: livestock, structures, railways, bridges, and orchards. Ultimately, parts of Ventura County lay under 70 feet of mud and debris. Over 500 people were killed, and damage estimates topped $20 million.

William Mulholland, an Irish immigrant who'd risen through the ranks of the city's water department to the position of chief engineer, had proposed, designed, and supervised the construction of the 238-mile Los Angeles Aqueduct, which brought water from the Owens Valley to the city. The St. Francis Dam had been one of the more controversial aspects of his plans. The dam was violently opposed by Owens Valley residents, who sabotaged its construction and often un-built portions overnight. The Aqueduct itself had been dynamited in 1924. The St. Francis Dam was Mulholland's 19th, and final, dam.

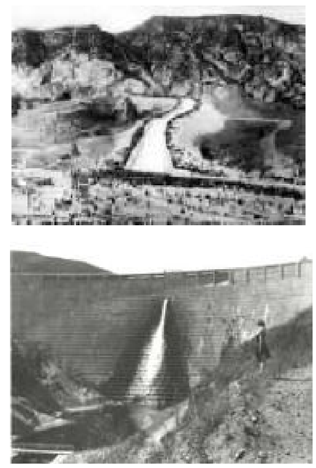


Figure CS5.1 St. Francis Dam; wreckage.

The St. Francis was a curved gravity concrete dam, designed to be 62 meters high. During construction, the height was increased by 7 meters to allow more water to be stored in the reservoir. No change was made to the other dimensions of the dam. In the days before the dam collapsed, the water level in the reservoir was only inches below the top of the dam.

At the subsequent inquest, it was demonstrated that the dam was leaking as late as the day before the collapse, and it was brought into evidence that the Department of Water and Power — and more importantly, Mulholland himself — knew it. Mulholland testified that he'd been at the dam the day before the break, but said that he hadn't noticed anything unusual. Leaks, he pointed out, were not particularly unusual in dams, especially dams as large as the St. Francis.

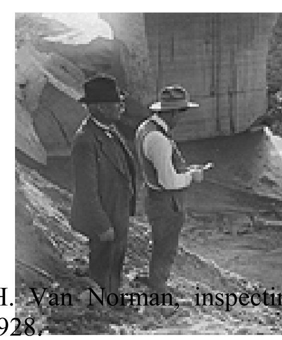


Figure CS5.2 Mulholland and H. Van Norman, inspecting wreckage at the Dam, March 15, 1928.

Although the assignation of cause and culpability is still a contentious subject among modern analysts, the 1928 jury ruled that the disaster was caused by the failure of a fault and rock formations on which the dam was built. Even so, the public held the DWP, and particularly William Mulholland, responsible. Although no criminal charges were brought against him, he retired from the DWP soon after the jury's verdict, and lived in self-imposed exile until he died in 1935, at 79 years old.

References

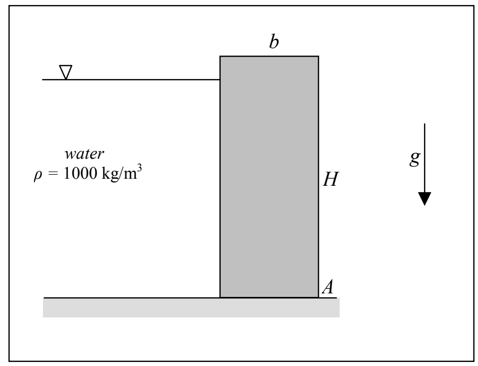
Davis, Margaret. "How the Hero Who Brought Water to L.A. Abruptly Fell From Grace," *Los Angeles Times*, July 25, 1993, p. M3.

Leslie, Margaret. *Rivers in the Desert: William Mulholland and the Inventing of Los Angeles*. New York: HarperCollins, 1993.

Mattson, Robert. *William Mulholland: A Forgotten Forefather*. Stockton: Pacific Center for Western Studies, 1976.

Problems

CS5.1 For a dam of height H = 62 m, thickness b, and width into the page w = 75 m as shown, made of concrete with density 2300 kg/m^3, retaining a body of water that is 60 m deep, find the net moment about point A and the minimum thickness of the dam that will prevent this moment from overturning the dam.



CS5.2 If the dam's height is increased to 70 m, and the water depth rises to 68 m, what thickness b is required to prevent tipping?

CS5.3 The St. Francis dam (with dimensions as in CS5.2) was observed to be leaking muddy water at its base, indicating that water was seeping under and around its supports. If water is allowed to penetrate freely under our model dam to point A, what thickness b is necessary to prevent the dam from tipping?

CS5.4 If we refined our model to more accurately represent the geometry of the St. Francis dam, including the curvature of the surface, would you expect the required thickness b to increase or decrease? Why?

Acknowledgments

The authors are grateful to colleagues Lori Bassman, Joe King, and Harry Williams, and to the students who have offered feedback on the eight offerings of Continuum Mechanics at Harvey Mudd College.

Bibliography

1. A. Bright and C. L. Dym, "General Engineering at Harvey Mudd: 1957–2003," *Proceedings of the 2004 ASEE Annual Conference*, Salt Lake City, UT, June 2004 (abstract accepted).
2. L. E. Grinter, "Report on the Evaluation of Engineering Education," *Engineering Education*, *46*, 25–63, 1956.
3. Catalog, Harvey Mudd College, Claremont, CA, 2003–05.
4. C. L. Dym, "Teaching Design to Freshmen: Style and Content," *Journal of Engineering Education*, *83* (4), 303–310, October 1994.
5. C. L. Dym and P. Little, *Engineering Design: A Project-Based Introduction*, 2nd Edition, John Wiley, New York, 2004.
6. J. R. Phillips and M. M. Gilkeson, "Reflections on a Clinical Approach to Engineering Design," *Proceedings of The International ASME Conference on Design Theory and Methodology*, Miami, FL, September 1991.

7. J. R. Phillips (Editor), *Engineering Clinic Issues*, Proceedings of the 30th Anniversary Symposium, Harvey Mudd College, Claremont, CA, 25 April 1994.
8. J. R. Phillips and A. Bright, "The Harvey Mudd Engineering Clinic: Past, Present, and Future," *Journal of Engineering Education*, *88* (2), 189–194, April 1999.
9. H. A. Simon, *The Sciences of the Artificial*, 3rd edition, MIT Press, Cambridge, MA, 1996.
10. P. D. Cha, J. J. Rosenberg and C. L. Dym, *Fundamentals of Modeling and Analyzing Engineering Systems*, Cambridge University Press, New York, 2000.
11. J. S. Rossmann and C. L. Dym, *Continuum Mechanics (Notes for E83)*, Department of Engineering, Harvey Mudd College, Claremont, CA, 2003.
12. Y. C. Fung, *A First Course in Continuum Mechanics*, 3rd Edition, Prentice Hall, Englewood Cliffs, NJ, 1994.
13. T. J. Chung, *Applied Continuum Mechanics*, Cambridge University Press, New York, 1996.
14. G. E. Mase, *Continuum Mechanics*, Schaum's Outline Series, McGraw-Hill, New York, 1970.
15. L.C. Brinson, T. Belytschko, B. Moran, and T. Black, "Design and Computational Methods in Basic Mechanics Courses," *Journal of Engineering Education*, *86* (2), 159–166, April 1997.
16. T. Belytschoko, A. Bayliss, C. Brinson, S. Carr, W. Kath, S. Krishnaswamy, B. Moran, J. Nocedal, and M. Peshkin, "Mechanics in the *Engineering First* Curriculum at Northwestern University," *International Journal of Engineering Education, 13*(6), 457-472, 1997.

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