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Software Tools for a Materials Testing Curriculum

Reference

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ABSTRACT

Instructors of both undergraduate and graduate courses of materials science with a laboratory section employ hands-on sessions to further students' understanding of key materials behavior principles. A typical solid mechanics laboratory session exposes students to topics such as: tensile, torsion, hardness, fatigue, and fracture testing procedures as well as associated properties and the like. Even though observing the different modes of material deformation and rupture response first-hand fosters a better mastery of the course content, limitations in available "face time" with students, course budget, availability of test devices, etc., are obstacles. Integrating software tools that simulate mechanical testing represents an alternative approach that can potentially transform and enhance the students learning outcomes. The identical graphical user interface is used for conducting both virtual and physical testing of materials. The software tools will aid in the classroom, laboratory, and student self-study for the subjects of a material's plastic

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yielding, stress-strain relationships, fatigue, crack growth, and fracture. These same tools are then used in the laboratory to perform physical testing. This integrated virtual/physical curriculum prepares the student in test setup, execution and data analysis and makes the laboratory experience more efficient. It is also instructive for gaining an understanding of the value and limitations of modeling approaches in describing material behavior.

Keywords
universal testing machine, console emulator, strength of materials, simulated data

Introduction

Instructional methodologies, especially those employed in the post-secondary educational stage, are constantly evolving to better engage students and to more adequately prepare them for the industrial workplace. A modern engineering curriculum not only combines both theory and practical application of engineering principles, but is also multi-mode to cater to the various learning styles of student audiences [1]. This contemporary mix of content and modes is synergistic with the industrial approach to problem solving (e.g., product development, failure reconstruction, etc.). Engineering workplaces often introduce a layer of simulation between theoretical design and actual prototype building.

Many engineering courses containing a laboratory component are inherently constrained because test devices are not always available to students to either: (1) adequately learn to use the device or (2) conduct a multitude of experiments. For example, students in a typical solid mechanics laboratory course having limited resources may only have a few hours from week-to-week to interact physically with a universal test device, its console, and test specimens. Despite the budget limitations that constrain many institutions, there is a tangible need for allowing engineering students more hands-on exposure to key test devices in their engineering coursework. Computational methods have advanced to the stage where simulations of experiments match real ones [2,3]. Embedding these numerical tools within a graphical user interface (GUI) allows instructors to bring a virtual test lab into the classroom and students to perform virtual tests prior to actually going into the testing laboratory. With regard to experiments concerning the mechanics of materials, all aspects of materials testing from test definition to test execution and data analysis should be performed without requiring actual test equipment or specimen. Others [4] have developed a software environment that included a simulation and visualization of the physical testing environment. The advantages of combining physical and simulated testing were described as giving students essentially unlimited access to experiments and facilitating study of many testing scenarios in a short period of time.

In this paper, we outline efforts to apply this integrated approach to a teaching curriculum for tensile, fatigue, and fracture testing of materials. Each of these three fundamental experiments of mechanics of materials is overviewed in the next sections with emphasis to instructional materials (i.e., lecture notes, laboratory testing instructions, homework assignments, test program definitions, test report templates and simulation definitions).

The Tension Test

Force, deflection, stress, and strain are all fundamental principles that engineering students acquire early in their studies and apply throughout their careers. For example, farm machinery such as plows or disks, must deflect under force, but with too much deflection the function of the machine will be lost. Automated packaging equipment must transmit power through rotating shafts and design engineers deficient in their knowledge of stress and strain will have broken parts to show for it. Understanding stress–strain relations is important, and that understanding is empirical in origin.

Experiments by Hooke and Young [5] and others over the past several hundred years established the basis for our modern definition of stress and strain or, in their time, force and extension. These experiments evolved into formal tests for determining material physical properties used by engineers to characterize the behavior of materials subjected to actual service conditions. It makes sense, then, to include a discussion of materials testing in the engineering curriculum.

One of the oldest and most useful material tests is the tension test, that is used to determine stress and strain and predict conditions that will cause failure. For tests to be repeatable, the test procedure must be well-defined. In the United States, the tension test for metals is specified by the ASTM International (American Society for Testing and Materials International) in test standard ASTM E8/8M [6]. The outcomes of this test include such useful properties as modulus of elasticity, yield strength, ultimate strength, and elongation at fracture, to name a few. The specimen is inserted into a tensile testing system capable of applying a uniaxial quasi-static force to the specimen, and equipped with sensors that monitor and record force and deformation from start to finish. As Hooke learned three hundred years ago, many metals have a linear relationship between the amount of force applied to a specimen, and the amount of resulting deflection. If the force is removed before it becomes too high, then the material returns to its original shape. If too high a force is applied, however, the specimen is permanently deformed even after the force is removed. In the latter case, the material *yielded* and the deformation changed from elastic to anelastic. In the elastic region, Hooke's Law, *ut tensio, sic vis (As the extension, so the force*), holds for a "linear" deforming material: stress is directly proportional to strain. This constant of proportionality is Young's modulus or the modulus of elasticity.

Students who perform physical tension tests learn the stress–strain relationship *experientally*. Their knowledge of Young's modulus is not just one of a dozen definitions to be memorized and soon forgotten. Engineering students learn about stress and strain the way Hooke and Young learned about stress and strain—

through direct experimentation and observation. Several hundred years of human experience are codified in the tension test, and actually running the test is the most direct means of acquiring an intuitive, as well as a mathematical, understanding of material behavior and its engineering description.

Tension Test Lecture

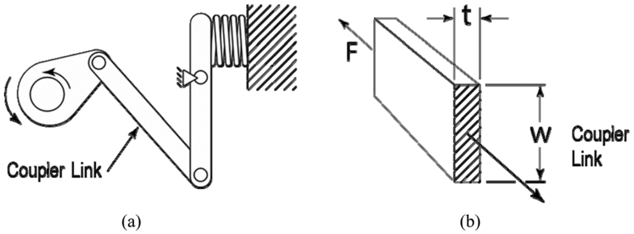
Simple examples and case studies are often effective for motivating students to learn the topic at hand. For a discussion on yield strength; for example, the design of a clutch linkage provides an excellent illustration. The coupler link in the linkage of Fig. 1 is a two-force member experiencing a 4.5 kN tensile force. If the force is too high, then the part will yield; that is considered failure. Students are asked to design the link by choosing an appropriate width *w* for a link made with a thickness, *t*, of 6 mm steel plate. To complete the design, though, students will need to know the yield strength of the steel plate. The laboratory section of the curriculum will teach the student how to measure the yield strength through measurement of the stress–strain curve and the calculation of the offset yield strength.

Test Equipment and Simulation

The test lab associated with this class uses an electromechanical Universal Test Machine powered by a DC servomotor and controlled by a digital closed loop controller. Test definition, execution, and communication with the controller are achieved via software running on a PC using Microsoft Windows. This software has a simulation mode that can be connected to a "virtual" test system to run tests on a range of "virtual" samples of different materials. The same software is installed on the lecturer's computer, the test lab computer, and in a student accessible computer lab. In that way, students can witness the test first virtual test in the classroom, and then perform their own virtual tests in the computer lab and finally perform actual test in the laboratory.

The introduction of simulation technology is beneficial to students as it provides an experiential link between the behavior of materials and physical

FIG. 1 (a) Coupler link and (b) dimension w to be determined.



phenomena, and illustrates how they can be described using engineering principles. The use of the Python [7] programming language makes the translation from equation to program easy to follow as the language has little "overhead" or abstraction. The code is written essentially in the same way as a manual calculation would be performed. Furthermore, Python is an open source language, so various samples programs and documentation exist in the open domain.

There are two basic materials supported in the current tension test simulation, steel, and acetal polymer. Upon starting the test, the student is prompted for which material to use for the specimen. The test is then performed in displacement control where a slowly increasing displacement is induced into the specimen until it fails. In simulation mode, the force response is simulated to respond appropriately for the selected material. The force signal is calculated from the displacement signal at the rate at which the data is collected. This is currently set up for 50 Hz, but can be set to any rate up to the controller update rate of 1024 Hz.

The simulation first converts the prescribed displacement signal into a strain signal using the following equation (terms in "`quotation marks and Courier font`" refer to the label of the term in the Python program example further below):

$$\varepsilon = dl/l_o \tag{1}$$

where:

ε = unitless measure of engineering strain, "`strain`"
dl = change of length (m), "`displacement_m`," and
l_o = gage length (m), "`GageLength`."

For steel, the strain signal is divided into 5 regions. Stress is related to strain using a spline curve fit: essentially a set of third order polynomials that relate stress to strain. An appropriate set of polynomial coefficients was determined for each segment of the curve from an actual tension test of mild steel. The acetal polymer curve fit was divided in to 7 regions, and again fit with a spline. As each displacement point is measured, it is compared with the boundaries of the region to determine which set of coefficients to use; stress at each displacement point is calculated using the appropriate set of coefficients.

The stress is then converted to force using the following formula:

$$F_n{=}\sigma/A, {''}stress^{\star}\ \mathrm{Area}{''} \tag{2}$$

where:

σ = normal stress (N/m^2), "`stress`,"
F_n = normal component force (N), "`SimulatedForce_Steel`," and
A = specimen cross section area (m^2), "`Area`."

Two of the five equations relating stress (y) to strain (x) for simulation purposes for steel are:

$$y = 207x;\ \text{from 0 to 0.130 m/m, region of Hooke's Law} \tag{3}$$

$$y = -0.101343x^3 + 7.90634x^2 - 205.235x + 2221.09;\ \text{from 24.9 to 36 m/m} \tag{4}$$

Below is the Python function that the simulation tool uses for calculating the force response for the simulated steel under elongation.

```
    def SimulatedFoad_Steel(displacement_m):
    strainCurve =[ 0.0, 0.130, 0.360, 1.3, 24.9, 36]
    coef1 =[ 0.0, 207, 0.0, 0.0]
    coef2 =[ 151.433785723072, 1214.621345688630,
−2871.363627044977, 2450.515601295664]
    coef3 =[ 239.453661520087, 435.466129855619,
−580.220664014717, 211.658303073500]
    coef4 =[ 291.492977403970, −2.337568897015,
0.946004094869, −0.024071351014]
    coef5 =[ 2221.091011391235, −205.234635658303,
7.906343158352, −0.101343125448]
    strain = displacement_m/GageLength* 100
    if (strain <= strainCurve[ 1] ):
         stress = Polynomial(strain, coef1)
    if (strainCurve[ 1] < strain and strain <= strainCurve[ 2] ):
         stress = Polynomial(strain, coef2)
    if (strainCurve[ 2] < strain and strain <= strainCurve[ 3] ):
         stress = Polynomial(strain, coef3)
    if (strainCurve[ 3] < strain and strain <= strainCurve[ 4] ):
         stress = Polynomial(strain, coef4)
    if (strainCurve[ 4] < strain and strain <= strainCurve[ 5] ):
         stress = Polynomial(strain, coef5)
    if (strainCurve[ 5] < strain):
         stress = 0.0
    stress = stress * 1000* 1000
    return stress * Area.
```

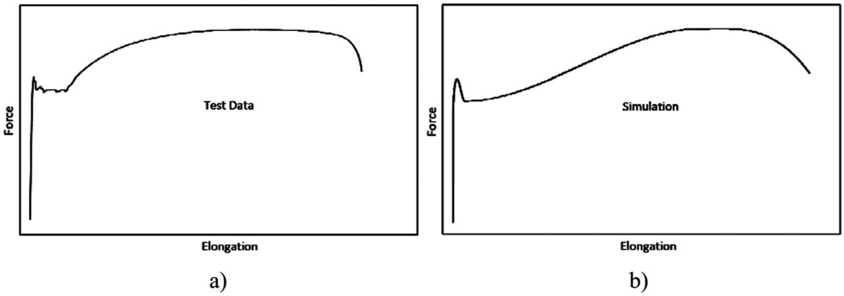
See Fig. 2 for actual test data and the approximation by the simulation via the Python function.

High Cycle Fatigue Test Lecture

The design for fatigue requires knowledge of a material's fatigue limit, defined as the fatigue strength at a fixed cyclic life. Unlike a tension test, the HCF test will require much more than 30–60 s to complete. If runout, or non-failure, is defined to be 10×10^6 cycles, an HCF test that cycles force at 30 Hz will require more than 90 h to complete. Simulation in this case is very useful for condensing the test and presenting the results quickly in the course of a lecture.

The tension test example considered static failure of the connecting link. For HCF, students will consider fatigue failure of the same link. For design

FIG. 2 (a) Actual test data (for a mild steel) and (b) simulated force–elongation curve.



purposes, the stresses must be compared to the fatigue limit of the steel. The fatigue limit for laboratory specimens has been found to be approximately half the ultimate tensile strength[6]. The fatigue test simulation is run during lecture, demonstrating runout for fully reversed forces that are less than half of the ultimate tensile strength.

It is possible to use the same simulation tool, albeit with different formulas, in the classroom demonstration of an HCF test. Time spent learning the behavior and the user interface can be applied uniformly for all of the materials tests. In an actual laboratory, of course, a servohydraulic load frame would be required. An electromechanical system uses motor-driven ballscrews to apply force and displacement to the specimen. This technology works well for quasi-static tests such as tension and fracture toughness where the force and the displacement are increased slowly and uniformly in one direction (the tensile direction, in these tests.) Dynamic tests such as high cycle fatigue require much higher loading rates, as well as high frequency direction reversals, and forces that can alternate between tension and compression. Backlash in ballscrews becomes an issue when switching from tension to compression. Loss of lubricant between ballscrews and bearings will result in heat generation and wear. Servohydraulic systems are far more appropriate for cyclic tests such as the high cycle fatigue test, and this is discussed in the laboratory section of the course.

Fracture Toughness Test Lecture

The fracture toughness test according to ASTM E399 [8] corresponds to a paradigm shift in design. Traditional engineering design uses a stress analysis approach to guard against overloads. The maximum stresses in a component are determined and in a first design approximation are compared to the yield strength (static

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[6] This is true for steels with an ultimate tensile strength less than 1380 MPa (200 ksi). For those steels whose strength is greater, the fatigue limit or fatigue strength at 10^6 cycles is approximated as $[1/2] \times 1380 = 690$ MPa (100 ksi).

failure), or the fatigue limit for cases with cyclic loading. This has been the traditional approach defined by Wöhler in the 1800s, and is still (albeit acknowledged by the authors to be an approximation) taught in engineering curricula today.

Fracture mechanics, on the other hand, is a relatively recent engineering development. Although the theory of linear elastic fracture mechanics was developed in the 1920s, widespread application of the theory had to wait until testing technology was able to provide designers with the corresponding material properties. This occurred in the 1960s, particularly in the aircraft and nuclear industries, and facilitated the development of damage tolerant design.

An important material property in damage tolerant design is the fracture toughness, K_{IC}. The fracture toughness is the critical value of the stress intensity "K" that results in failure by catastrophic fracture, and as such it is given the subscript "c" for "critical." (The Roman numeral "I" in K_{IC} stands for mode one opening displacement.) Instead of comparing the worst-case stresses to the yield strength, the designer compares the stress intensity (K) to the fracture toughness (K_{IC}). Designers often perform this comparison to determine the critical crack length in the component under design. Like the tension test, the fracture toughness test entails a monotonic, quasi-static ramp. The mode of control is force control, rather than strain or displacement control. The specimen has been pre-cracked prior to the test, so the failure force corresponds to the force that causes an "atomistically sharp" crack to propagate to failure. This failure force is used to calculate the corresponding critical value of the stress intensity ($K = K_{IC}$).

Fracture toughness tests can be performed using either servohydraulic test systems or electro-mechanical test systems. This lecture on fracture toughness incorporates the electro-mechanical system simulation used in the previous two materials tests. The fracture force is determined using the 5 % offset line, and the fracture toughness is calculated from the fracture force in accordance with ASTM E399. The simulation provides a very effective demonstration of the similarity between the tension test and the fracture toughness test: students who understood the tension test can easily grasp the fracture toughness test. This provides an excellent learning path for advancing from the traditional, intuitive understanding of stress and yield strength to the newer concepts of stress intensity and fracture toughness.

Integration

For mechanics of materials laboratory students, thrusting the task of learning new software on top of their homework, lab report writing, and other responsibilities might be counterproductive by further diluting their focus on mastering core concepts. A more strategic approach to integrating software mastery is needed. In tensile testing, the pre-lab homework could, for example, contain the following tasks:

- With regards to mechanics of materials, define the following terms: (1) necking, (2) proportional limit, (3) elastic limit, (4) fracture stress, (5) % reduction area, etc.

- Acquire the material properties of the candidate material being used (e.g., modulus, yield strength, tensile strength, and Poisson's ratio).
- Develop the dimensions of a test specimen that complies with ASTM E8/8M-11 [6].
- Use the virtual testing software to develop simulated test results for the candidate material. Verify that the simulated data is in agreement with the defined mechanical properties.

It should be noted that the software can include "helper text" to illuminate concepts as the student is running the experiment. One source for terminology used in experiments in mechanics of materials is available via Ref. [9]. This would reduce the number of resources students might have to consult.

In the lab session, the instructor would assume the students have had some level of interaction with the software and would thus show less obvious aspects of the GUI, i.e., displacement control versus force control, data acquisition rates, etc. Actual tensile tests would be performed and students could analyze the specimen and the data. In the corresponding lab report, the student would be tasked with analyzing data generated in the lab session, and possibly generating additional simulated data under conditions that might vary from those used in the lab session. Topics such as rate-dependence, temperature-dependence, and so on, that are not typically covered could be studied in great depth with this virtual testing tool.

Another level of integration between classroom learning and engineering work is reached by exposing students to the use and development of standards. One useful resource that will be integrated into this materials testing curriculum is the ASTM Professor Tool. These are learning materials that ASTM makes available to the public on their website, without license, to teach on the subject of standards use.

Conclusion

There are a number of advantages to this integration of lecture presentation, simulation, and physical testing. As discussed earlier, students have a direct experience with the material property needed to successfully complete their design exercise. It also provides a direct illustration of material behavior (elastic versus inelastic deformation, ductility, yield failure, fracture failure, energy absorption). These, in turn, can serve as a discussion prompt for more advanced concepts: why does a material yield? What makes a material ductile as opposed to brittle? Define ductility. Why are some materials stronger than others? What if we designed our link out of plastic instead of steel?

Furthermore, students become familiar with test methods, learn testing concepts, procedures, and vocabulary, collect and interpret data and extract property values, and identify where empirical results are used in an engineering analysis. This approach therefore prepares students to perform actual material tests.

Another advantage of giving students access to all tools in a simulation environment is that they can learn at their own pace rather than in a lab setting with limited machine and specimen availability.

Engineering students like to see the connection between what they learn in school and what they do in industry. Design examples requiring knowledge of material properties provide both a context and a motivation for learning, and the empirical nature of our knowledge of material properties makes it important to bring the materials test into the classroom where it belongs.

Simulation plays a growing role in any industrial development process and exposure to its capabilities and limitations should therefore be part of any lecture on design.

It is the authors' belief that the integration of instruction, simulation, and hands-on interaction with a physical specimen ensures better understanding and therefore prepares students best for work in the global engineering market.

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