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Pull, Twist, and Break: Helping Engineering Students Visualize Material Failures

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Abstract

The materials tested in basic engineering mechanics courses, such as steel and aluminum, have been well studied and have consistent material properties. Experimentally testing these materials in a laboratory setting helps students visualize the difference between the failure behavior of ductile and brittle materials. However, there are thousands of other materials which are commonly used in industry and academia which exhibit different behaviors or are more inconsistent between samples. These materials may behave differently when subjected to different loading conditions such as tension, torsion, or impact. Many colleges and universities might not have the equipment to conduct these experiments, the resources to purchase different materials, or the time to conduct a large variety of tests in class or in a laboratory course. This project investigated the development of visual aids to help students better understand the behavior of a wide variety of materials under various loading conditions. There were three specific types of visual aids that were created. The first was a display board where undeformed and failed samples due to uniaxial tension, pure torsion, and impact for 12 different materials were mounted for students to observe side to side. The 12 different materials included steel, aluminum, cast iron, ABS (3D printed at different orientations), acrylic, wood, and others. The second type of visual aid was high speed videos of failure under uniaxial tension and pure torsion. The third visualization was photoelasticity videos of acrylic samples which highlight stress concentrations in experimentally loaded samples. These visualizations may be used in introductory courses such as Mechanics of Materials or advanced courses such as Manufacturing and Machine Component Design. This paper will detail the design and creation of each of the visualizations. Future research will assess the impact these visualizations have on student comprehension of different material behaviors and failure modes.

Introduction

Research has shown that active learning and hands-on activities greatly improve students' understanding and comprehension of challenging material [1]. The ability to utilize their senses of sight, touch, and hearing when learning about the behavior of materials and structures increases their ability to apply their knowledge. Improving a student's spatial skills and ability to visualize complex problems has been shown to improve retention and performance in engineering courses [2]. Hands-on mechanics demonstrations and activities have been utilized for decades [3], [4], [5], [6], [7]. Recently, educators have developed tutorials and databases to assist other educators looking to incorporate these hands-on activities into their own courses [8]. Even professional societies such as the American Institute of Steel Construction (AISC) have invested significant resources into developing hands-on and virtual resources for educators to use [9]. As technology has improved, the development of educational videos or virtual resources has become widespread. Researchers have released videos of failures, finite element and behavior simulations, and technical content videos [10], [11], [12], [13], [14], [15], [16].

In 2008, Timothy Philpot et al. released their first edition of the textbook "Mechanics of Materials: An Integrated Learning System [17]." Coupled with this textbook release were visualization tools called "MecMovies" developed using Macromedia Flash 5 software [12]. These videos allowed students to interact with the course content as they progressed through the curriculum. In 2019, the Efficient Engineer began to release video animations explaining many complex mechanics topics [18]. Now researchers are investigating the use of augmented and virtual reality for mechanics education to visualize 3D mechanics problems and load paths [19], [20], [21].

However, most of the educational tools and training aids which exist today are focused on fundamental topics or conventional material behaviors. As industry advances, education must progress simultaneously. For example, a new mechanics design laboratory course developed physical demonstrations for machine components [22]. These demonstrations could be used by students in hands-on activities demonstrating threaded fasteners, bearings, gears, pressure vessels, tolerances, finite element modeling, and mechanical failures. The ability to visualize these course concepts greatly improved students' learning. As material development in industry, manufacturing, and commercial applications expands beyond the use of traditional materials such as steel, aluminum, cast iron, and concrete, curriculum on material behavior and failure will also have to advance. Current undergraduate curriculum only briefly introduces advanced materials such as additively manufactured materials and plastics. With the increased proliferation of additively manufactured and plastic components, training aids are due for modernization. Research has shown the importance of incorporating additive manufacturing into education [23]. Advancements such as fused deposition modelling (FDM) present a perfect opportunity to educate students on the behavior, analysis, and design of nonhomogeneous and anisotropic materials.

Educators typically use in-class testing and laboratory exercises as an opportunity to introduce students to the behavior and failure mechanisms of materials under different types of loading. The types of loading vary from axial tension and compression, torsion, flexure, and impact. The cost and time requirements to complete these hands-on experimental tests on multiple materials can be extensive. Small undergraduate institutions may not have the equipment necessary to experimentally test specimens under each of these different types of loading. They may also only have access to traditional materials such as steel and aluminum and may not have the capability to additively manufacture or machine different specimens. Time is most likely the most limiting factor. Traditional courses on mechanics of materials have blocks dedicated to axial loading, torsional loading, flexural loading, combined loading, and theories of failure. With all the course content which must be covered during traditional lecture sessions, each block of the course may have only enough space to conduct a single laboratory session. Therefore, during this constrained period, the instructor or students may only have time to test one or two materials, which continue to be dedicated to traditional materials.

Recently, researchers have investigated the use of virtual laboratories to offset the challenges with planning and resourcing physical hands-on laboratories [24]. Virtual laboratories can be used to demonstrate bending moment, torsion, and transverse shear loading on simple structures as well as complex aircraft components. However, virtual laboratories lose some of the benefits realized from in-person, physical hands-on experiences. Simulations also include perfect execution and may not capture critical assumptions needed for experimental tests.

The research question which this study aimed to answer was "Can training aids be developed to help student visualize failure of non-traditional materials under various loading conditions to compliment laboratory programs?" The study presented in this manuscript investigated the design and development of three visualization strategies to help undergraduate students understand the behavior of different materials under three different loading conditions: uniaxial tension, pure torsion, and impact. The three visualizations included a physical display board with different materials tested under various loading conditions, a database of videos documenting the failure of different materials, and photoelasticity images capturing stress distributions of specimens under loading. This manuscript documents the goals, resources, and outcomes of each of these visualizations.

Design Methodology

To ascertain the materials required for a modern display board, the authors surveyed faculty of engineering mechanics courses at the United States Military Academy. Faculty were asked to identify common materials and failure modes utilized in discussions, engineering problems, exams, and demonstrations within their courses. From this elicitation, it became clear that visualizations of traditional materials such steel, aluminum, cast iron and concrete were insufficient to meet the wide variety of materials used. The authors ultimately identified ten unique materials, two heat-treatments, and two additive manufacturing processes for inclusion in the study. This resulted in 16 different specimens. The samples utilized were aluminum, steel, cast iron, brass, fused deposition modeling with acrylonitrile butadiene styrene (ABS) [vertical and horizontal orientation], stereolithography resin (SLA) [vertical and horizontal orientation], annealed steel, quenched steel, acrylic, polycarbonate (PC), polyethylene terephthalate (PET), ABS, nylon, and wood.

While the study was limited to these 16 specimens, the design presented may be used to customize the visualizations for an educator's individual requirements. To reduce the cost of the study, the materials were all sourced from existing laboratory supplies or on-site additive manufacturing capabilities. This allowed the students to see the same material samples throughout their undergraduate curriculum, beginning with Fundamentals of Engineering Mechanics and Design course (Statics), again during each of their hands-on laboratory experiences, and finally during their culminating capstone experience. The authors sought to link past in-class experiences to hands-on exploratory learning to reinforce learning objectives and create continuity through course progression. In addition to material selection, loading was considered for each specimen. Faculty were asked to identify failure modes common to design problems or material discussions. The limit states of uniaxial tension, torsion, and impact were initially selected. Other limit states such as combined loading, fatigue and buckling were omitted, but could be included in future studies.

Specific courses considered for use of the visualizations were MC300, Fundamentals of Engineering Mechanics and Design; MC364, Mechanics of Materials; ME403, Manufacturing and Machine Component Design; MC380, Engineering Materials, and the Capstone Design course. The enrollments for the 2023-2024 academic year are shown in Table 1.

Table 1: Enrollment in courses during the 2023-2024 academic year

Course	Mechanical Engineer Enrollment	Civil Engineer Enrollment	Total Enrollment	Class Year
Fundamentals of Engineering Mechanics and Design (Statics)	91	32	149	Sophomores
Mechanics of Materials				
Manufacturing and Machine Component Design	79	0	79	Juniors
Engineering Materials	84	0	120	Seniors
Capstone Design		36		

Physical Material Failure Board

The first visualization which was created was a physical display board to show material failure under the various loading conditions. The inspiration for the display board is shown in Figure 1. This historical board was created in 1952. It included impact, tension, torsion, shear, and compression samples permanently affixed to the board. The tension included an undeformed specimen, two different grade steel specimens, and one each aluminum, brass, and cast-iron specimen. The torsion section included only an undeformed specimen and steel and cast iron tested specimens. The impact section included three Rockwell tests on steel specimens. The compression tests included a short and a tall column. A single sheared bolt was also affixed to the board. Each of the specimens included an engraved plaque with the type of material, dimensions, type of test, and strength of the material.

When designing the new board, the authors considered the interactive and standalone nature of the display board. In terms of the layout, three variations were considered. The first was to create three separate boards for each different loading condition: uniaxial tension, torsion, and impact. This type of board would be more portable and could be used in each course without overwhelming the students with such a large board. However, it would also require more management and maintenance due to the requirement to bring three boards to a single class. Additionally, there are no redundancies for misplaced or broken samples. The second option was to have a board for all metal samples and one for all polymer samples. However, one of the primary objectives of the study was to introduce students to advanced materials. The third option was to include all materials and loading conditions on a single board. This would allow entry-level students to be exposed to advanced materials and treatments early in their curriculum. It would also allow experienced students to review fundamental failure modes of basic engineering materials. A single display board, that encompassed the materials of choice for both civil and mechanical engineering students, would inspire curiosity and appreciation for the breadth of materials, different post-processing treatments, and considerations in advanced manufacturing techniques. Additionally, placing all samples on one board improved logistical requirements of management and maintenance.

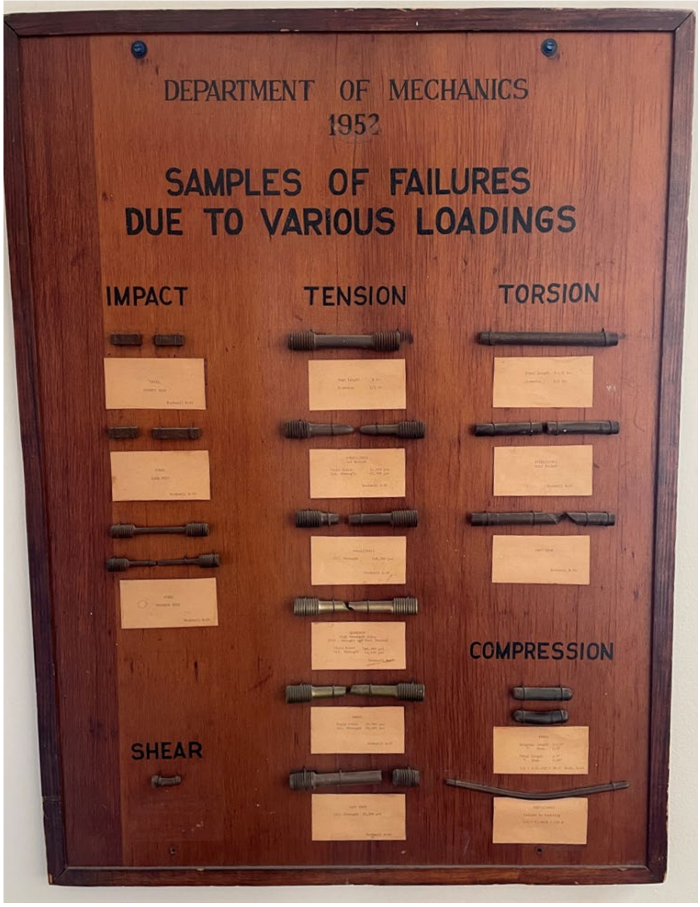


Figure 1: Historical display board of material failures under various loadings

The display boards were designed to be 30 inches by 36 inches made of ¾ inch plywood. A total of 64 samples were displayed on each board, with each material displaying an undeformed, tension, torsion, and impact tested sample.

The materials and equipment used to test the specimens were sourced from the undergraduate materials testing laboratory. It was decided to use the same specimen dimensions for the tension and torsion testing. Manufacturing was required to adapt the specimen to the various testing apparatus. For the metal and additive materials, a ¼ inch cylindrical coupon specimen was used with hexed ends to fit a 7/16 inch 6-point socket as shown in Figure 2b and Figure 3b. For the polymer and wood samples, a 3/8-inch cylindrical coupon specimen was used with hexed ends to fit a ½ inch 6-point socket as shown in Figure 2a. The polymer and wood samples required additional machining at each end to utilize the sockets as shown in Figure 2a. A Computer Aided Design (CAD) was developed to print the additively manufactured specimens as shown in Figure 3a. The samples were manufactured using a Stratasys F370 printer with ABS material. Heat-treatments were applied to the specified steel samples on-site. This process utilized an L&L Special Furnace Co, Inc furnace and took 16 hours to anneal. The Charpy V-notch samples were notched using a Blacks Charpy hand operated notch machine. The notch in the additively manufactured specimens was included in the CAD file and printed into the specimen.

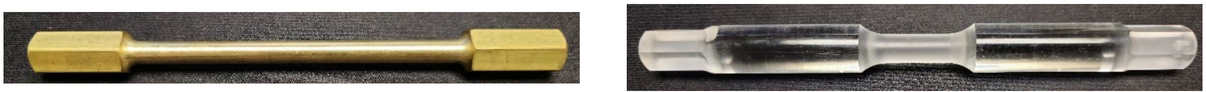

(a) (b)

Figure 2: Cylindrical coupon specimen with 3/8 inch 6-point hexed ends: (a) Standard for all metal and printed specimens; (b) modified for polymer and wood specimens.

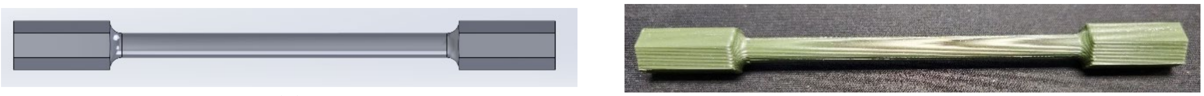
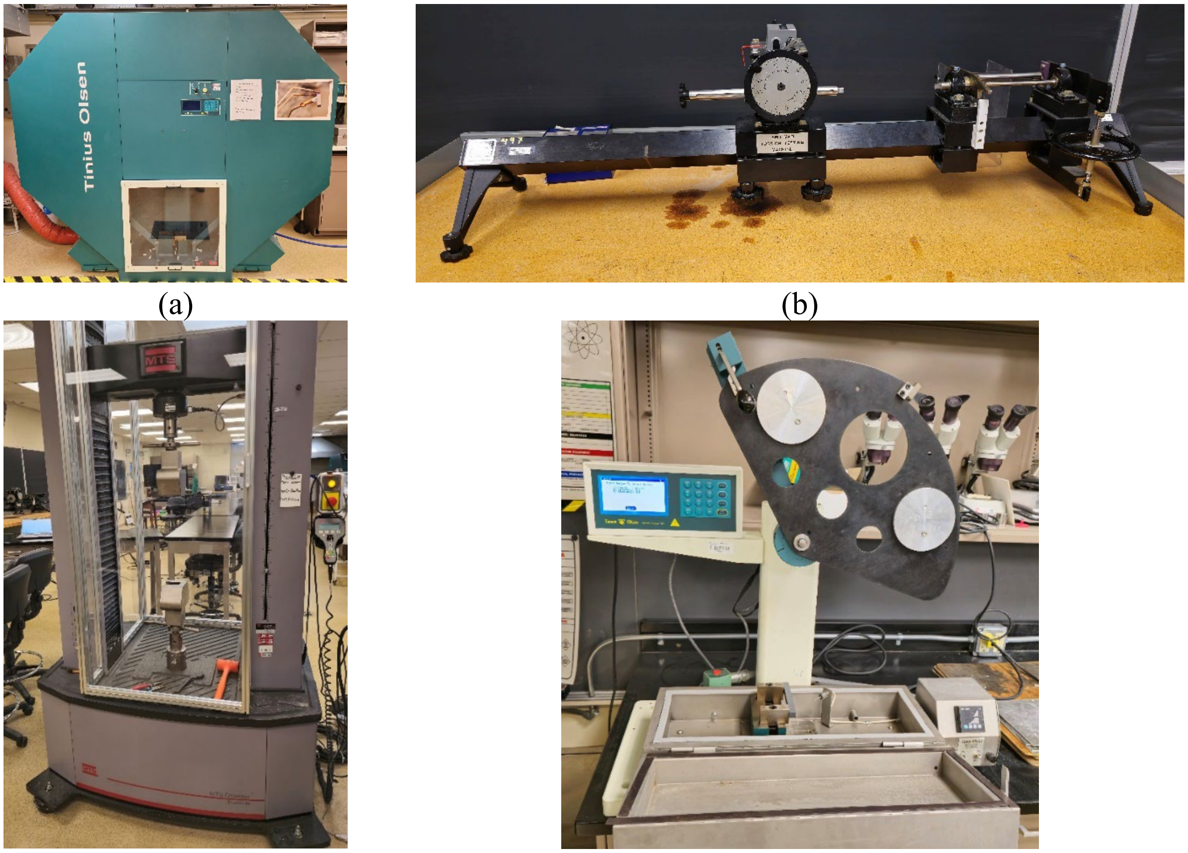

(a) (b)

Figure 3: Additively manufactured specimen: (a) CAD model; (b) Final specimen

Three unique testing devices were utilized for each test. A Material Testing System (MTS) universal testing machine was used to test the specimens under uniaxial tension as shown in Figure 4c. However, for the purpose of building the display samples, no data was recorded during testing. An alternative option could be to use a TecQuipment Universal Testing Machine or similar tension testing device. A manual TecQuipment Torsion Testing Machine was used for torsion testing as shown in Figure 4b. A metal Tinius Olsen Charpy Impact Tester was used for impact testing as shown in Figure 4a and a plastic Olsen Charpy Impact Tester was used for impact testing on plastics as shown in Figure 4d.



(a) (b)

(c) (d)

Figure 4: Material Testing Machines: (a) Metal Charpy Impact Tester; (b) TecQuipment Torsion Machine; (c) MTS Universal Testing Machine; (d) Plastic Charpy Impact Tester

To maximize student interaction and hands-on learning, the samples were designed to be removable from the display board. The instructor team evaluated different mounting options for the board and opted to have removable grips to facilitate portability and accessibility of the board compared to bulky boxes or trays. Custom specimen holders were designed and additively manufactured to both aid in students' ability to remove the specimens and to secure them to the board. While the specimens are exposed and may be damaged or collect dust, it was deemed to be more important for students to interact with and handle the specimens. Custom holders for the cylindrical specimens are show in Figure 5a and for the Charpy impact specimens are shown in Figure 5b.

Additionally, the authors considered adding plaques for each sample similar to those shown in the original board on Figure 1 including the name, grade, strength, and ductility of each of the specimen.

(a) (b)

Figure 5: Additively manufactured custom specimen holders: (a) Cylindrical specimens; (b) Charpy impact specimens.

High-Speed Videos

As previously stated, the value of in-person, hands-on laboratory testing is due to the student's ability to see, hear, and feel the specimens during and after testing. The physical display board allowed students to feel and see the failed specimens after testing. However, the behavior of the material during testing is not captured. During in-person laboratory sessions, it is difficult to ensure that all students are engaged and able to actively participate and view the experiment. To ensure each student was able to view the behavior of the material during testing, high speed videos were recorded for each material under tension and torsion.

During the uniaxial tension and torsion tests, a Photron FASTCAM SA-X High Speed Video camera was used to capture failure of the specimens. The test setup with the camera and light sources are shown in Figure 6. Ensuring the camera captured the failure event was a critical component of tensile and torsion testing, as the manual trigger relied on operator reaction speed to catch the failure. An "end" trigger was used, where the manual trigger signified the end of the recording. The procedure was to use an initial camera setting of 3,000 frames per second for all testing. If successful capture was conducted on the first specimen, subsequent tests fine-tuned frame rate and recording time to capture optimal failure imagery.


(a) (b)

Figure 6: High speed camera experimental setup: (a) Tension tests; (b) Torsion tests.

Optically Active Acrylic For Stress Fields

The third visualization was to capture photoelasticity by videoing acrylic specimens subjected to tension and torsion loading. Isotropic bodies subject to a two-dimensional stress, while within their elastic limit, will reflect light like a doubly refracting crystal [25]. The authors used two polarizing filters; one between the camera and the specimen and one at a ninety-degree orientation to the other between the specimen and a light source, as shown in Figure 7 for both tension and torsion tests. Due to the directional light requirements and the resulting low light, a standard video camera at 60 frames per second was utilized for video capture. Additionally, the authors did not utilize the high-speed camera for capture because it only records black and white video. This negates the capture of visually stunning and stimulating images.


(a) (b)

Figure 7: Photoelasticity setup: (a) Tension tests; (b) Torsion tests.

Results

Physical Material Failure Board

The final material failure display board is shown in Figure 8. The authors elected to build three display boards. It was decided not to include plaques to avoid inundating the display with too much information. The authors determined the excess information would detract from the fundamental aim of the project. The name of the material was laser engraved into the plywood for each material. The board would be utilized by different courses on different lessons. With small section sizes of a maximum of 20 students, some courses have simultaneous sections, which require their own board. The interactive nature of the display board allowed for the removal of the specimens. Students may compare failure modes between different materials, allowing them to view failed specimens from a different perspective. During classroom or laboratory activities, each sample may be passed to each student. The display boards could also be used as an assessment of student learning by having the students position the specimens in the correct location on the board. This could assist with reinforcing identification of failure modes for basic materials or assessing student understanding of ductile versus brittle materials by comparing the failed specimens to the undeformed specimens. The students can easily observe the conical failure shape of ductile materials such as steel and the clear transverse failure of brittle materials such as cast iron when tested in tension compared to the transverse failure of ductile materials and the 45-degree angled failure of brittle materials. Use of the display boards in courses was intended to supplement laboratory experiments and demonstrations as opposed to replacing in-person activities. The boards can be used to reinforce and assess the behavior of materials. Due to material limitations, the final product did not include impact tests for several samples. This will be completed during future work.

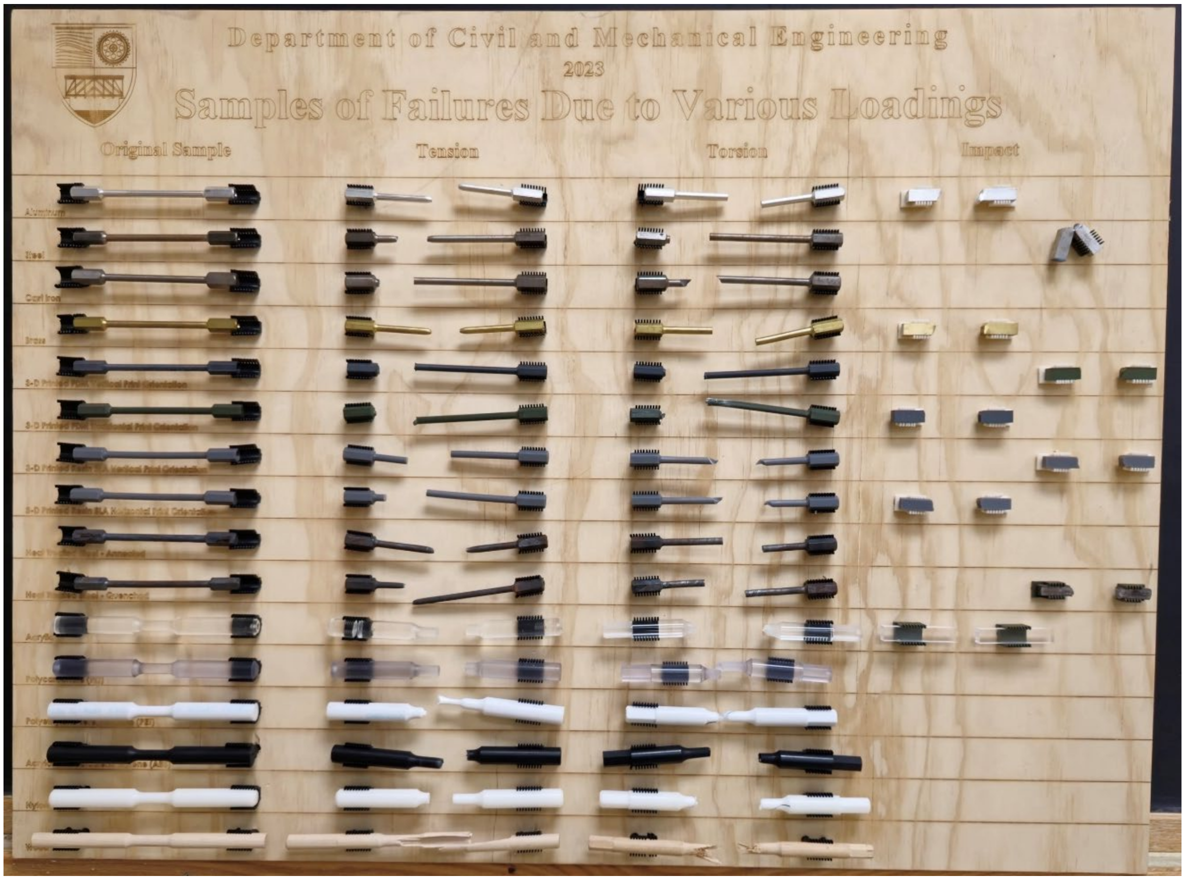


Figure 8: Physical material failure display board

High-Speed Videos

Slow motion video helped capture the behavior of each material at failure, allowing for students to personally view testing. Typically, during a laboratory activity, many of the students do not have a good vantage point. The actual failure may occur rapidly and be hard to see with the naked eye, especially for brittle materials. Visually observing laboratory experiences reinforces critical knowledge on the behavior of materials. Understanding elastic and plastic deformation, necking, strain hardening, yield and ultimate strength are essential properties necessary to effectively design with different materials. Slow motion videos provide insight into the failure modes of materials, which is difficult to catch during live experiments. By viewing these videos both before and after in-person laboratories, students may gain a greater appreciation of material behaviors. Additionally, the cost required to execute one video series is a single expenditure that can be re-used for years to come. Faculty may reference these videos throughout the curriculum. Lastly, with the rising costs of certain materials, such as cast iron, a single purchase can fuel student learning for years to come.

Uniaxial tension failures are foundational concepts for civil and mechanical engineering students. The classic material demonstration of brittle versus ductile failure can be demonstrated by comparing the behavior of a cast iron specimen and a ductile steel alloy specimen as shown in Figure 9. The ductile steel material exhibited a distinct necking region with a classic cup-and-cone 45-degree failure due to shear [26] as shown in Figure 9a. The ductile specimen will demonstrate plastic deformation before failing along the shear plane [26]. The brittle cast iron material shows the immediate 90-degree failure plane at circled at the bottom of the coupon in Figure 9b. Just the physical samples don't demonstrate indications of failure. The brittle specimen has very little warning of failure due to crack propagation initiated at microscopic flaws in the cast iron.

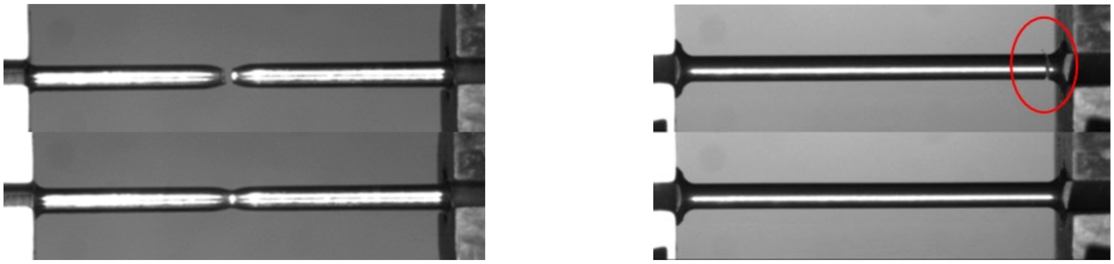

(a) (b)

Figure 9: Screen capture from slow motion video of specimen failure in uniaxial tension: (a) Ductile steel; (b) Brittle cast iron

When observing the torsion tested specimens, the opposite behavior is observed. The steel (Figure 10a) exhibits a 90-degree failure plane due to pure torsional shear, but the cast iron (Figure 10b) exhibits a 45-degree failure plane due to the maximum principal stress due to tension. These demonstrations help compare shear and tensile strength between ductile and brittle materials [26]. Making high-speed videos available, in conjunction with static display boards, provides further learning for those students whose curiosity is stimulated.

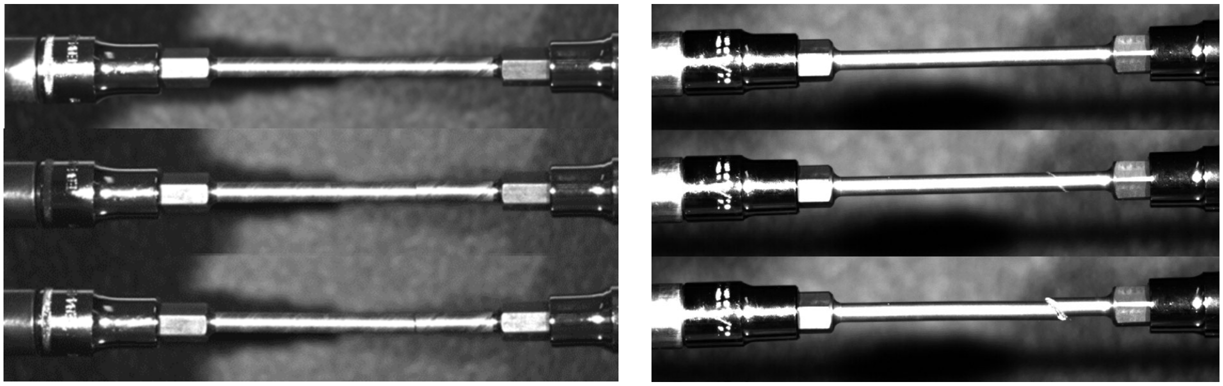

(a) (b)

Figure 10: Screen capture from slow motion video of specimen failure in torsion: (a) Ductile steel; (b) Brittle cast iron

Testing of polymers emphasized the behavior of ductile versus brittle materials. Uniaxial tension tests for two different polymers are shown in Figure 11. The Polyethylene terephthalate (PET) material (Figure 11a) experienced exaggerated necking due to polymer chain orientation and axial strain compared to the steel sample and an ideal cup-and-cone failure mode. The nylon material (Figure 11b) experienced a pure brittle failure. This behavior can be used by instructors when discussing material selection and specifications for polymers. Tensile specimens can be used to demonstrate regions where polymer chains become oriented parallel to the elongation direction and strengthen (Figure 11a)[27]. Additionally, comparisons of thermosets, thermoplastics, and elastomers can be drawn from visual inspection of low strain-rate failure planes. If desired, display boards can display stress vs. strain curves, Elastic Modulus, Engineering Yield Strength, reduction in area, or toughness to further reinforce specific course motifs at a university.

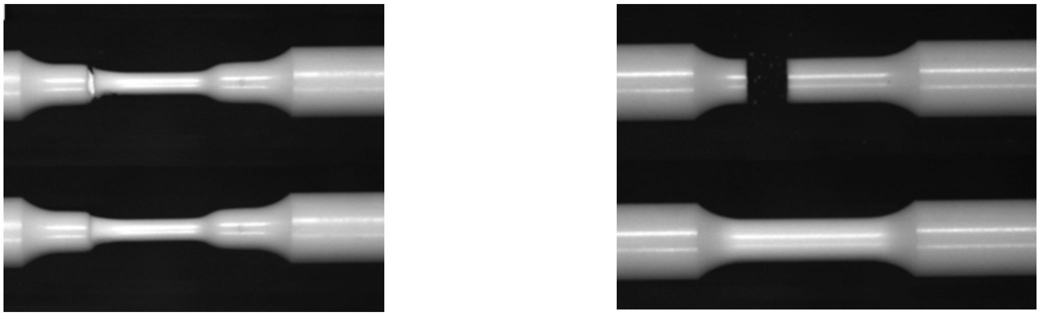

(a) (b)

Figure 11: Screen capture from slow motion video of specimen failure in uniaxial tension: (a) Polyethylene terephthalate (PET); (b) Nylon

The slow-motion videos were also used to capture unique and catastrophic failures. Failure of acrylic in torsion was captivating as well as informative as shown in Figure 12. Students can identify the energy stored in the elastic deformation of the specimen. Students can visualize the deformation as the material transitions from clear to opaque. Additionally, what better way to excite students than showing catastrophic failure of materials?

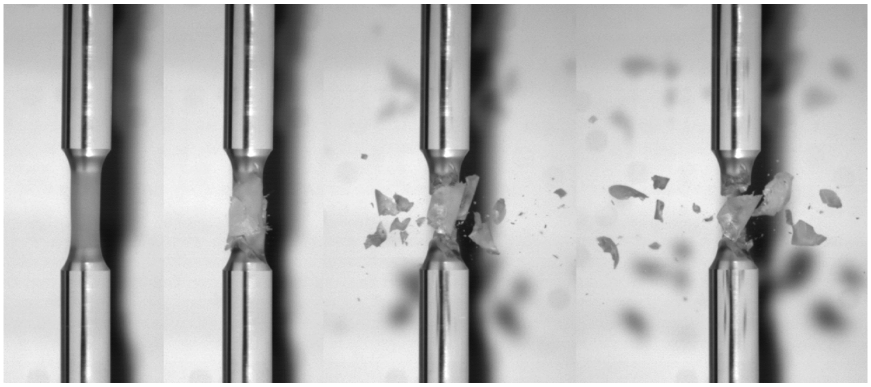
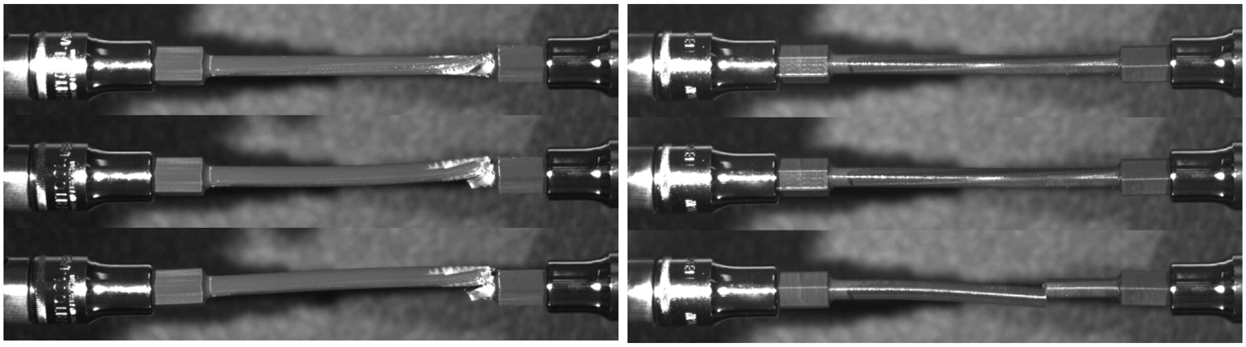


Figure 12: Screen capture from slow motion video of acrylic specimen failure in torsion

A critical component in the appreciation of fused deposition modeling capabilities is understanding the impacts of print parameters on part performance. Viewing the failure on a physical display board only allows students to identify differences between the failure modes. However, providing high-speed video of failure helps students view the failure progression and load transfer during testing. The videos highlighted crack propagation through layers of the FDM specimen for the ABS with horizontal fibers shown in Figure 13a. Creating layer lines along the primary shear plane of a component leads to very little plastic deformation of the fibers and results in no early warning of failure as show in Figure 13b. The slow-motion videos provided context for failure of composites, such as wood. Unique grain boundaries and fiber patterns results in unique splintering of wood samples as shown in Figure 14. For civil engineering students, wood failure samples provided context for expected failures of common construction materials with respect to grain direction.



(a) (b)

Figure 13: Screen capture from slow motion video of FDM ABS specimen failure in torsion: (a) Horizontal fibers; (b) Vertical fibers

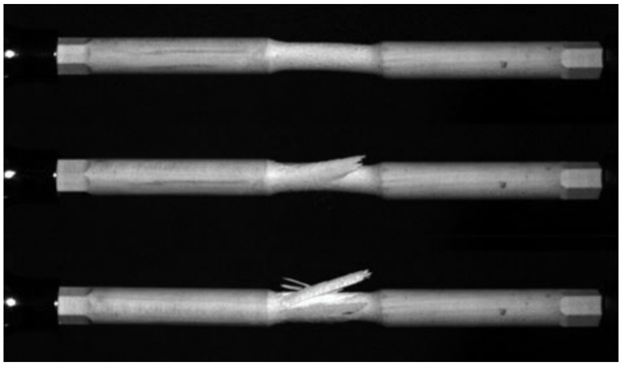


Figure 14: Screen capture from slow motion video of wood specimen failure in torsion

In this study, 13 specimens were tested and videoed in tension and in torsion. No slow-motion capture was conducted for steel heat treatments or polycarbonate due to the authors late decision to add those specimens to the display board. Additionally, manually triggering the camera resulted in several missed failures. However, in creating three display boards, the authors had three chances to catch the failure event. If capture of the failure event was successful, subsequent testing events utilized varied camera settings to achieve greater video resolution. Shooting higher frame rate video results in lower resolution and shorter recording time. Each video was limited in size. As such, high frame rate recordings would only capture a fraction of a second of material failure. While beneficial for catastrophic brittle failures, the high-speed video often missed plastic deformation and necking that occurred in ductile materials. With a focus on visualizing failure, the authors elected to capture the failure event in slow motion.

Optically Active Acrylic For Stress Fields

Photoelasticity provides for captivating images of acrylic failures with stress and strain contours. The screen-captures shown in Figure 15 highlight the stress in the material to help students visualize internal stress concentrations and the mechanics of specimen under tension or torsion. The impacts of radius and second polar moment of area on shear stress are highlighted through stark variations in color and varying rate of color change in the samples. In the video, a change in color denotes an increase in stress, which demonstrates that the reduced cross-section experiences increased stress in comparison to the larger cross-section. This is highlighted especially for the tension specimen in Figure 15a. As the middle portion of the coupon experiences increased strain, the cross-section decreases due to the effects of Poisson's ratio. This results in rapid color change sequences during testing. The change is consistent throughout the shaft of the coupon due to the brittle nature of the acrylic material and lack of localized necking. At failure, the photoelasticity video showed the material relieving internal stress, but after failure the results of residual stresses and strains can still be seen in the specimen. For the torsion specimen, there is less distinct changes in color along the shaft since the diameter of the cross-section does not change. However, the plastic deformation can be seen when the specimen becomes opaque and no longer exhibits photoelastic properties. Photoelastic video reinforces variations in the manifestation of stress concentrations in uniaxial tension versus pure torsion. While this example of photoelasticity utilizes round members, flat members can be added to the display board to emphasize impacts of various features as they relate to stress concentrations in uniaxial tension.

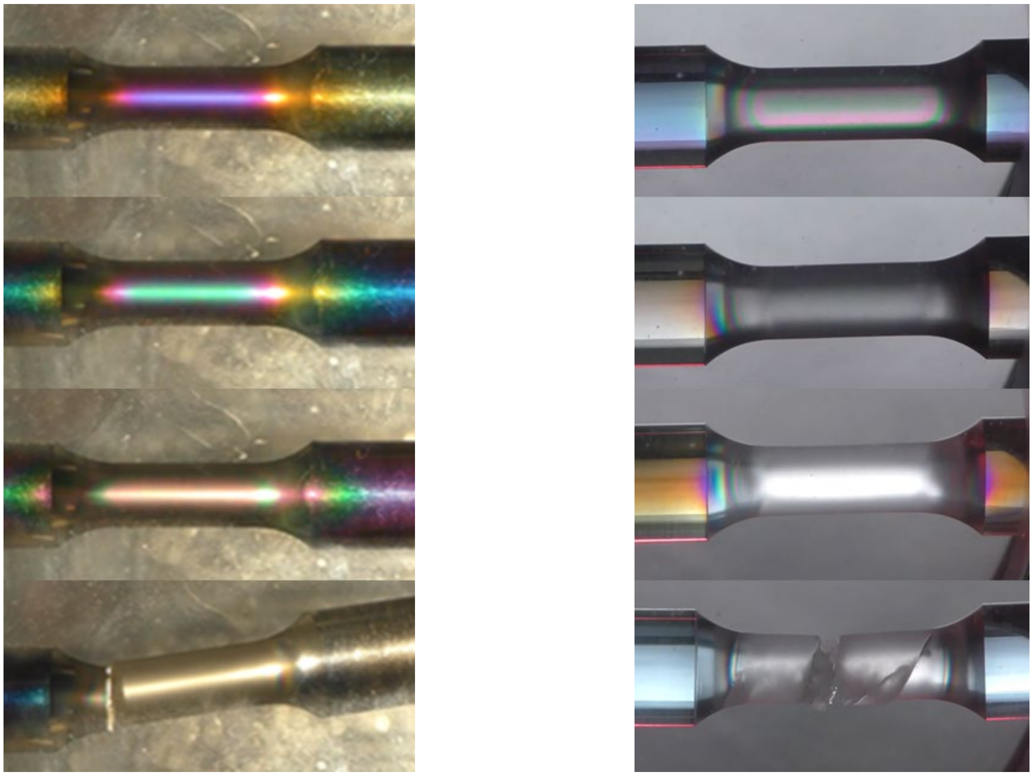

(a) (b)

Figure 15: Photoelasticity analysis of acrylic specimen: (a) Uniaxial tension; (b) Pure torsion

Discussion & Future Work

The purpose of this study was to document the process of creating three different visualizations to help students better understand material failure. The impact of these three visualization demonstrations on student performance has yet to be assessed. However, throughout this process, the authors have identified several areas of improvement. The first recommendation would be to utilize a standard camera for capturing specimen failure in conjunction with a high-speed camera. Additionally, clearer imagery can be captured with the use of an optical zoom rather than a digital zoom. For brittle failures, the high-speed camera was necessary to capture the milliseconds of failure. However, for the ductile materials the increased frame rate of the high-speed cameras limited the capture time to several seconds; the high-speed camera omitted the initiation of necking and plastic deformation. While these demonstrations focused on failure and identifying failure surfaces, much can be gained by capturing the entire failure sequence on camera. It is recommended that those who re-create this project record ductile failures with both high-speed video and a normal 60-120 fps, 1080p or 4k resolution camera.

Additionally, this display board was completed utilizing specimens available on-site that are currently utilized for various hands-on labs. If procuring new materials solely for the purpose of creating a display board, it is recommended to secure clear plastics, and un-polished specimen. The higher surface roughness would result in less glare captured on the video. Recording slow motion video required external light-sources, which made capturing usable images difficult on smooth round specimens due to their reflective surfaces. Another limitation of this study was that tests were conducted using different cameras and different testing machines both manual and mechanical, which limited the ability to use time, recorded force, or deformation data for each of these visualizations.

In future editions of this research, advancements may be made to enhance the quality of the visualization. Additional data could be added to the display board including material strength and strain data. A high-quality camera and universal testing machine could be used for testing. This would allow for each specimen to be loaded at a similar load rate to correlate force vs deformation and stress vs strain data. During the video of the experimental testing of the material, a live graph could be created to display the stress-strain curve. A QR code could also be included on the display board to provide students with easier access to information, videos for each specimen, and close-up photos of the failure surface. Future research could explore developing virtual reality opportunities for students to interact with 3D scans of the specimens if it is not feasible to have the physical display board present. Future work may also include having audio voiceovers accompany the videos to narrate the behavior of the materials during testing and provide supplementary context. Lastly, this study investigated using the same round specimens for both tension and torsion testing, however using rectangular cross-sectional specimens for the photoelasticity tension tests.

The authors plan on assessing the impact of these visualization on students' performance in future semesters. The authors will develop a survey to determine if these visualizations helped the students better understand the course material and effectively design components based on their material properties and behavior. The authors will also assess the impact of the visualizations on students' performance by comparing results on course assessments for students who used the visualizations compared to students who did not.

Conclusions

Pulling, twisting, and breaking are excellent hands-on experiences for engineering students. Building of a static display board created opportunities to customize modern and persistent teaching demonstrations. Hands-on displays introduce fundamentals to first year students, while creating awareness of post-processing and additive manufacturing techniques. Additionally, a comprehensive physical display created an enduring classroom demonstration in engineering materials courses. The creation of a static display also introduced opportunities to capture failure in motion, which can excite, educate, and explain failure modes and behaviors of materials. However, only providing static samples limits student learning to the result of the failure mode. Visualizing the failure mechanisms in slow motion allows students to assess crack propagation, compare ductile and brittle failures, see individual fibers fail in FDM printed parts, and gain a deeper understanding of material behaviors. Lastly, inclusion of photoelasticity reinforces a topic first introduced 93 years ago by Max Frocht; visualizing stress can be affordably resourced in engineering schools [25]. What better way to build better engineers than to break things in the process?

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References

[1] S. Freeman *et al.*, “Active learning increases student performance in science, engineering, and mathematics,” *Proc Natl Acad Sci U S A*, vol. 111, no. 23, pp. 8410–8415, Jun. 2014, doi: 10.1073/pnas.1319030111.

[2] S. A. Sorby, “Developing 3D spatial skills for engineering students,” *Australasian Journal of Engineering Education*, vol. 13, no. 1, pp. 1–11, Jan. 2007, doi: 10.1080/22054952.2007.11463998.

[3] J. L. Klosky and R. Vander Schaaf, “Hands-On Demonstrations in Introductory Mechanics,” in *ASEE Annual Conference and Exposition*, Montreal, Canada: American Society for Engineering Education, Jun. 2002.

[4] D. Flaherty, “The Use of Physical Models and Demonstrations in Engineering Education,” University of Colorado, Boulder, 2017.

[5] R. Borchert, D. Jensen, and D. Yates, “Development and Assessment of Hands-on and Visualization Modules for Enhancement of Learning in Mechanics,” in *ASEE Annual Conference and Exposition*, Charlotte, NC: American Society for Engineering Education, Jun. 1999.

[6] J. Kadlowec, P. Von Lockette, E. Constans, B. Sukumaran, and D. Cleary, “Hands-on Learning Tools for Engineering Mechanics,” in *ASEE Annual Conference and Exposition*, Montreal, Canada: American Society for Engineering Education, Jun. 2002.

[7] A. A. Lumsdaine, “Design of Training Aids and Devices,” *American Instiutes for Research in the Behavioral Sciences*, 1960.

[8] “Hands-On Mechanics.” Accessed: Feb. 04, 2024. [Online]. Available: https://www.handsonmechanics.org/

[9] AISC, “Educator Forum,” American Institute of Steel Construction. Accessed: Feb. 04, 2024. [Online]. Available: https://educatorforum.aisc.org/home/

[10] S. Shakerin and D. D. Jensen, “Enhancement of mechanics education by means of photoelasticity and finite element method,” *International Journal of Mechanical Engineering Education*, vol. 29, no. 4, Apr. 2000.

[11] J. Thomas, R. Hall, T. Philpot, and D. Carroll, “The Effect of On-Line Videos on Learner Outcomes in a Mechanics of Materials Course,” in *ASEE Annual Conference and Exposition*, Vancouver, BC: American Society for Engineering Education, Jun. 2011.

[12] T. Philpot, N. Hubing, R. Flori, R. Hall, D. Oglesby, and V. Yellamraju, “Computer-Based Instructional Media for Mechanics of Materials*,” *International Journal of Engineering Education*, vol. 19, no. 6, pp. 862–873, Sep. 2003.

[13] S. Reynolds, “Seeing Structures: Interactive CAD Models in Mechanics of Materials,” in *ASEE Annual Conference and Exposition*, Virtual: American Society for Engineering Education, Jul. 2021.

[14] J. Wood, D. Jensen, and K. Wood, “Enhancing Machine Design Courses Through Use of a Multimedia-Based Review of Mechanics of Materials,” in *ASEE Annual Conference and Exposition*, Portland, OR: American Society for Engineering Education, Jun. 2005.

[15] S. C. Cooper and G. R. Miller, “Suite of computer-based tools for teaching mechanics of materials,” *Computer Applications in Engineering Education*, vol. 4, no. 1, pp. 41–49, 1996.

[16] L. Dobrzański, A. Jagiello, and R. Honysz, “Virtual tensile test machine as an example of Material Science Virtual Laboratory post Education and research trends,” *Journal of Achievements of Materials and Manufacturing Engineering*, vol. 27, no. 2, Apr. 2008.

[17] T. Philpot and J. Thomas, *Mechanics of Materials: Integrated Learning System*. John Wiley & Sons, 2020.

[18] “The Efficient Engineer.” Accessed: Feb. 04, 2024. [Online]. Available: https://www.patreon.com/efficientengineer

[19] A. Hain and S. Motaref, “Evaluation of Augmented Reality as a Visualization Tool to Enhance Undergraduate Engineering Students’ Performance in an Entry-Level Course,” *Journal of STEM Education*, vol. 24, no. 2, 2023.

[20] C. Hedenqvist, M. Romero, and R. Vinuesa, “Improving the Learning of Mechanics Through Augmented Reality,” *Technology, Knowledge and Learning*, vol. 28, no. 1, pp. 347–368, Mar. 2023, doi: 10.1007/s10758-021-09542-1.

[21] J. A. Torres, A. Sychterz, and J. Henschen, “Enhanced Learning of Load Path in a 3D Structural System using Virtual Reality,” in *ASEE Annual Conference*, Minneapolis, Minnesota: American Society for Engineering Education, 2022. [Online]. Available: www.slayte.com

[22] S. Marra, “Development and evolution of a new mechanical design laboratory course,” in *ASEE Annual Conference and Exposition*, Indianapolis, IN: American Society for Engineering Education, 2014.

[23] T. Serdar, “Educational Challenges in Design for Additive Manufacturing,” in *ASEE Annual Conference and Exposition*, New Orleans, LA: American Society for Engineering Education, 2016.

[24] W. Tsutsui *et al.*, “Enhancing Students’ Understanding of Deformation and Stress in Aerospace Structures Education via Virtual Labs,” in *ASEE Annual Conference and Exposition*, Minneapolis, MN: American Society for Engineering Education, Jun. 2022.

[25] M. Frocht, “Recent Advances in Photoelasticity: And an Investigation of the Stress Distribution in Square Blocks Subjected to Diagonal Compression,” *Transactions of the American Society of Mechanical Engineers*, vol. 53, no. 2, 1931.

[26] R. L. Norton, *Machine Design: An integrated Approach*, 6th ed. Hoboken: Pearson, 2020.

[27] W. D. J. Callister and D. G. Rethwisch, *Materials Science and Engineering: An Introduction*, 9E ed. Hoboken: Wiley, 2014.