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Seeing Structures: Interactive CAD Models in Mechanics of Materials

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Abstract

When COVID-19 necessitated remote teaching, mechanics faculty needed to quickly convert hands-on teaching props into equally effective online equivalents. This constraint sparked a new innovation in a Mechanics of Materials course. Unable to pass around a foam beam to demonstrate concepts such as "plane sections remain plane," or an annotated wood cube to illustrate the sign convention for shear stress, dozens of interactive CAD models were developed with the open-source browser software SketchUp. The CAD models have been uploaded to SketchUp's 3D Warehouse and placed in the public domain. They are opened by students in browser windows and are manipulated in 3D space. Familiarity with the modeling software led to a second innovation: the presentation of exam problems in SketchUp. In an exam, students are provided with a hyperlink to a CAD model in the public domain. Students navigate the model in 3D space, note key dimensions, and perform requested calculations. Assessment of the impact of these innovations is ongoing in Fall 2020, as the 2D problems used on paper exams in prior years are now being presented to students in full 3D. This paper will explain how this approach is easily accessible to all faculty, including those with minimal CAD experience. Additionally, the public-domain 3D models will be demonstrated, and links shared, so that these visualizations may be used at other institutions and shared across the engineering education community.

Introduction

In March 2020, COVID-19 (a contagious disease caused by a novel coronavirus) disrupted higher education in the United States. Prior to the pandemic, many aspects of the traditional engineering classroom prevailed across universities. For example, in the pre-pandemic Mechanics of Materials classroom, many professors used board notes to deliver content to students. For example, consider a rigid beam supported by deformable cables (Figures 1, 2).

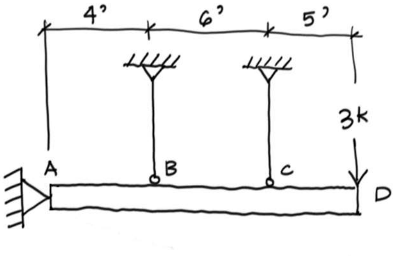


Figure 1. Rigid Beam Supported by Deformable Cables (Undeformed, Drawn by Hand)

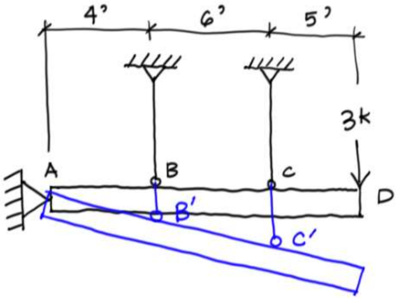


Figure 2. Rigid Beam Supported by Deformable Cables (Deformed, Drawn by Hand)

This type of visual communication was likely drawn on any number of dry erase boards in engineering classrooms around the world. As in-class drawing is relatively time-consuming, instructors were likely to make the drawing process as efficient as possible, perhaps overlaying the deformed geometry on top of the undeformed geometry, using a different color to differentiate between the two ideas (Figure 2).

These diagrams are both symbolic and analytical. They are drawn in a language only comprehensible to those that possess a certain fluency: “While … three-dimensional objects, students are generally taught about these objects through static, two-dimensional illustrations in textbooks and on the classroom board. As educators, we have an understanding of the components and processes that constitute our discipline … we can visualize these things in our mind’s eye. One of the initial challenges we face is conveying our visual understanding to our students” [1].

The abrupt pivot to remote teaching and learning in 2020 sparked a new innovation in a Mechanics of Materials course at Colorado School of Mines. Course lectures would be delivered via videoconference by necessity. The constraint of teaching online created an opportunity to modernize visual communication through the use of CAD (computer-aided design) modeling software. The rigid beam problem was reimagined as an interactive model (Figures 3, 4, 5, 6).

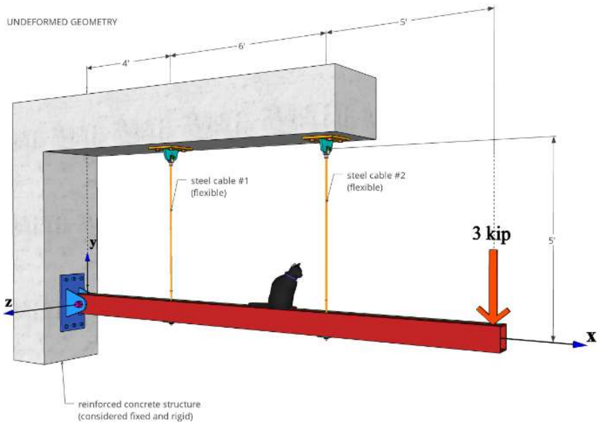


Figure 3. Rigid Beam Supported by Deformable Cables (Undeformed, Modeled in CAD)

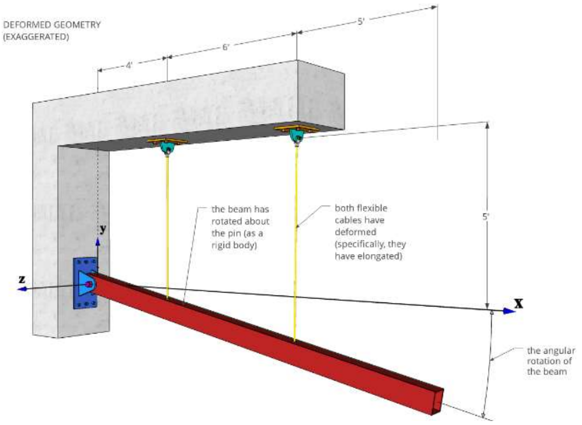


Figure 4. Rigid Beam Supported by Deformable Cables (Deformed, Modeled in CAD)

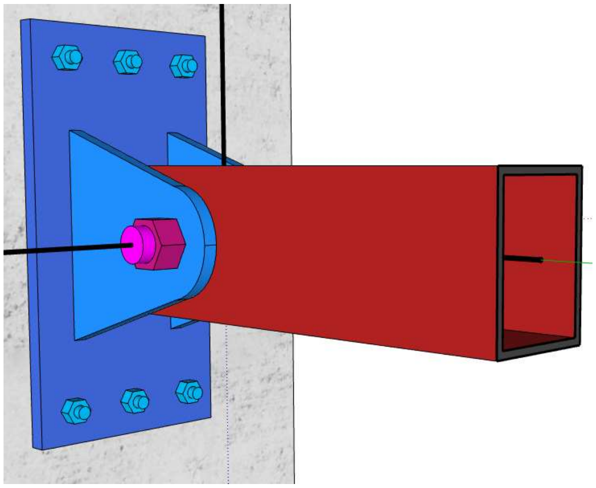


Figure 5. Plate connection between steel beam and concrete column (Detail from Interactive CAD model)

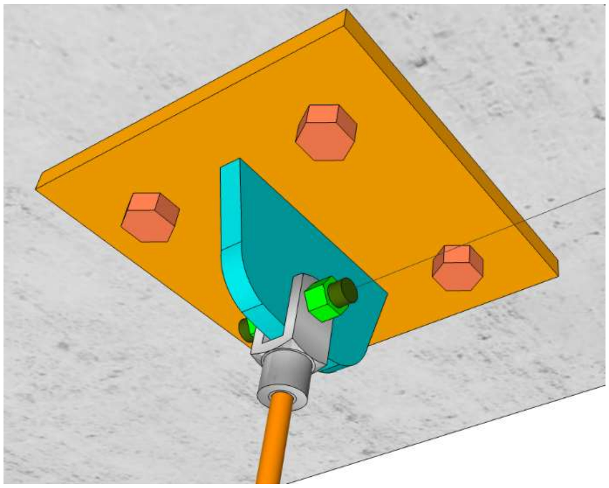
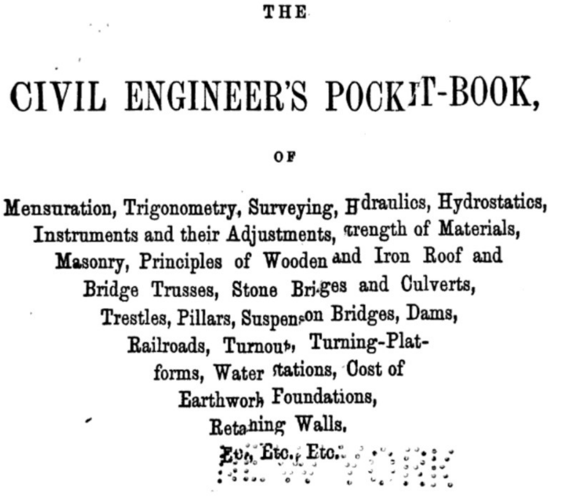


Figure 6. Clevis-to-cable connection (Detail from Interactive CAD model)

This particular CAD model [2] supports student learning in three ways. First, it enables visualization of the deformed geometry in three-dimensional space, directly supporting a course learning outcome. Second, students observe details that show how the structure could be built. That is, the abstraction of the analytical model and practicality of the construction detailing are viewed and explored concurrently. While generally not a course learning outcome for an engineering mechanics course, this knowledge and skillset is an important aspect of engineering practice that students should attain over the course of their undergraduate studies. Lastly, in the realm of meta-communication, students are provided with an example of effective visual communication. Learning by example, they may emulate this type of visual communication in upper-level courses and beyond. This contributes to ABET (Accreditation Board for Engineering and Technology) student outcome 3, "an ability to communicate effectively with a range of audiences."

Visual communication in engineering mechanics pedagogy

The motivation to effectively communicate complex visual and spatial ideas in the realm of engineering mechanics has been well-documented in the literature and in the evolution of textbook design. For instance, the cover of John C. Trautwine's "pocket-book" for Civil Engineers (the 1874 edition, public domain) boasts its "650 engravings from original designs" (Figures 7, 8) [3].



THE

CIVIL ENGINEER'S POCKET-BOOK,

OF

Mensuration, Trigonometry, Surveying, Hydraulics, Hydrostatics,
Instruments and their Adjustments, Strength of Materials,
Masonry, Principles of Wooden and Iron Roof and
Bridge Trusses, Stone Bridges and Culverts,
Trestles, Pillars, Suspension Bridges, Dams,
Railroads, Turnouts, Turning-Plat-
forms, Water Stations, Cost of
Earthwork Foundations,
Retaining Walls,
Etc., Etc., Etc.

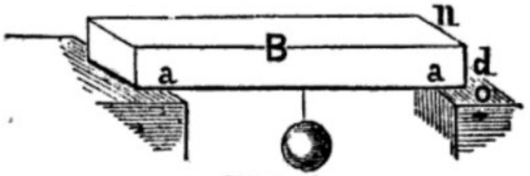


Fig.4

Figure 7. Cover image, Trautwine's 1874 Civil Engineer's Pocket-Book, public domain, [3]

Figure 8. Engraved image of beam behavior, Trautwine's 1874 Civil Engineer's Pocket-Book, page 183, [3]

A discussion of modern visual communication for engineering mechanics would be remiss without citing traditional published textbooks. According to Moore and Reinsfelder [7], the R. C. Hibbeler [4] [5] and Beer & Johnson [6] texts comprise the majority of assigned textbooks in Mechanics of Materials classes. The team's conclusions were based on a random sample of 80 colleges and universities (20 two-year colleges, 20 undergraduate-only institutions, 20 public research universities, and 20 private research universities) [7]. The illustrations in these traditional textbooks – while comprehensive and professional – remain two-dimensional images on a screen or a page.

In the early 2000s, Philpot et al. [8] began initial explorations into the use of 3D, animated, and interactive CAD visualizations for mechanics courses. With a preliminary focus on statics, this team of researchers created visualizations in Macromedia Flash (known as Adobe Flash, or simply Flash). Their motivation was to support students that "have difficulty visualizing structures and solution methods presented in traditional lectures." Flash was chosen in order to keep file sizes manageable and because it permitted interactions with a user in a browser [8].

Building on that work, in the mid-2000s, Philpot et al. [1] developed a website and software suite to support instruction in Mechanics of Materials. The aptly named "MecMovies" site was built with Flash and consisted of "over 110 animated example problems, drill-and-practice games, and interactive exercises." MecMovies remains widely known among engineering mechanics faculty to date [9], [1].

In that same time period, Dollár et al. [10] developed a web-based Engineering Statics course that included multimedia animations and simulations. This team also chose Flash as the most appropriate software for this purpose. The multimedia aspects of the web-based Engineering Statics course were largely developed in two dimensions, yet effectively communicate abstract concepts. Furthermore, the interactive models often require the user to make and test hypotheses, such as those related to static equilibrium [10].

Around 2013, V. Carbonell et al. [11] demonstrated the use of Geogebra (a graphical software principally intended for use with visualization of mathematics principles) as a tool for engineering mechanics. Geogebra was used to teach selected two-dimensional concepts, such as the parallel axis theorem and Mohr's Circle for stress transformation [11].

Around 2014, Rhoads et al. created the "Purdue Mechanics Freeform Classroom," a "new approach to engineering mechanics education" that combines "largely traditional lectures, hybrid textbooks/lecture notes, extensive multimedia content, course blogs, and refined student assessment tools" [12]. One aspect of the project is the "Visualizing Mechanics" section of the website. The visualizations seem to be largely videos that focus on experimental (and computational) concept demonstration [13].

In 2020, technology companies (Microsoft, Apple, etc.) removed Flash from web browser capabilities, rendering it obsolete. Developers are expected to recreate web-based interactive visualizations in HTML5. The removal of Flash has rendered the MecMovies website inaccessible and work is underway to replace the Flash visualizations in Engineering Statics with HTML5 equivalents [14], [15].

In summary, this literature review identified two leaders in the realm of web-based interactive/animated visualizations for engineering mechanics: MecMovies [14] and Engineering Statics [15]. The work described in this paper, *Seeing Structures*, is the first-generation of a new, online repository of interactive teaching models that facilitate visualization of engineering mechanics problems. The project scope includes content from Statics, Mechanics of Materials, and Structural Analysis. To date, the majority of the models have been created to support a Mechanics of Materials course at Colorado School of Mines.

Pre-COVID teaching props and their *Seeing Structures* equivalents

Pre-COVID mechanics classes often relied on tactile, hands-on props. As society is newly sensitive to the possibility of viral infection, passing tactile props around a room of students may no longer be acceptable social behavior. Three pre-COVID teaching props have been chosen for a direct comparison with their *Seeing Structures* counterparts: planar shear stress (Figures 9, 10), torsional shear stress (Figures 11, 12), and stress on an inclined plane (Figures 13, 14).

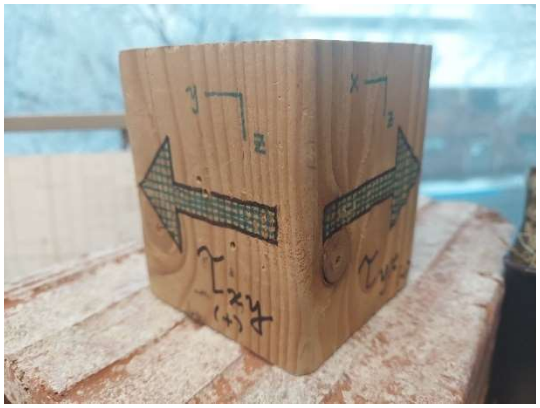


Figure 9. Planar shear stress: pre-COVID teaching prop (hand-drawn symbols on a wood cube)

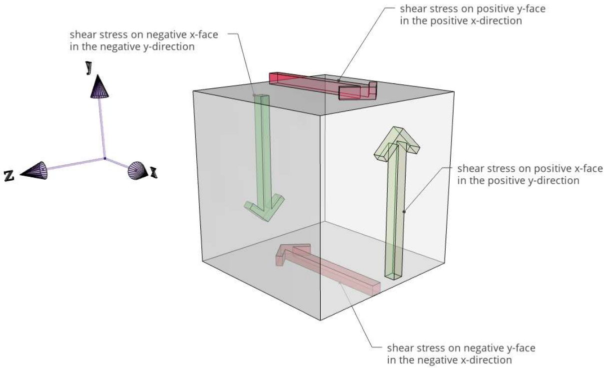


Figure 10. Planar shear stress: *Seeing Structures* visualization [16]

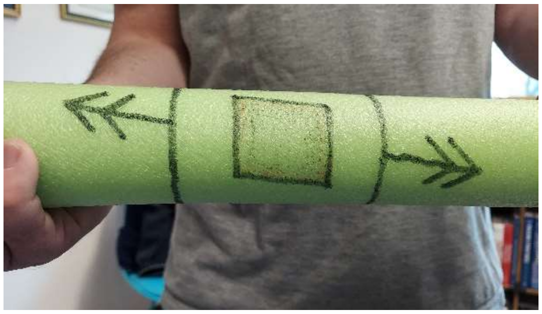


Figure 11. Torsional shear stress: pre-COVID teaching prop (hand-drawn lines on a foam member)

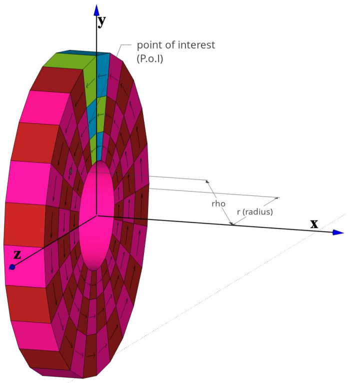


Figure 12. Torsional shear stress: *Seeing Structures* visualization [17]

Figure 13. Stress on an inclined plane (hand-drawn images on a wood member)

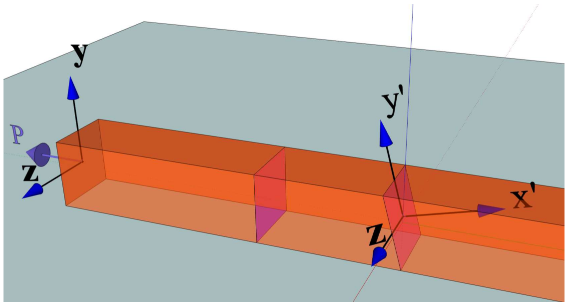


Figure 14. Stress on an inclined plane: *Seeing Structures* visualization [18]

All three of these concepts are notoriously difficult for engineering students to master. Outsiders to this field may be surprised to learn that the difficulty in applying these concepts is not related to complex mathematics. Rather, the difficulty in applying these ideas is usually related to visualization.

Access to the *Seeing Structures* repository of CAD visualizations

The *Seeing Structures* repository of CAD models (Figure 15) is accessible to the public and may be viewed at *https://3dwarehouse.sketchup.com/user/441016d8-1ab3-4d6b-9547-9c1b21cb30c9/Seeing-Structures* [19]. The visualizations are accessible in any browser. Each is interactive: the model may be manipulated during class by the professor or out-of-class by the student.

Furthermore, a menu of views (e.g. undeformed, deformed, column connection, clevis connection) as well as robust panning/orbiting abilities provide a three-dimensional environment for students to explore at their own pace. Each view has been programmed by the author to reveal or hide certain elements, cut cross-sections through the geometry, or zoom in to details. No special education or skillset is needed to navigate the model in a browser window. The interface is both simple and intuitive.

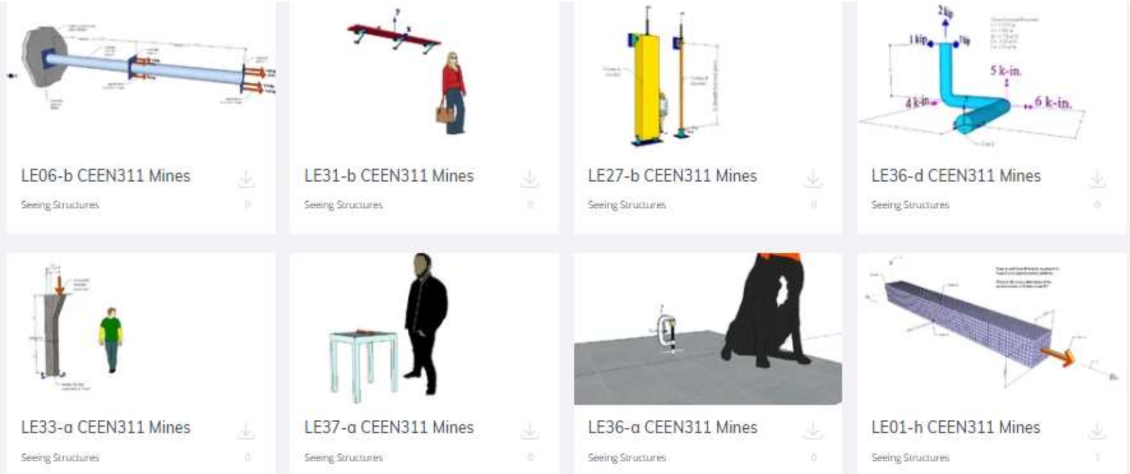


Figure 15. Sample thumbnail images of the *Seeing Structures* repository of CAD Models

Table 1 contains a compilation of the models created in 2020. All were created to support a Mechanics of Materials course, although several topics (e.g. centroids, sign conventions for shear force and bending moment) are also applicable to other mechanics courses such as Statics.

Table 1. Current List of *Seeing Structures* CAD Visualizations

Title	URL
1. Internal normal force, shear force, and bending moment in a beam element	https://3dwarehouse.sketchup.com/embed/f96138d3-07a0-40e6-9f3e-bd1bbb3accb9
2. Average normal stress	https://3dwarehouse.sketchup.com/embed/e04721f4-a4c5-473b-ba8d-03cc694f8b6c

3. The stress cube and the stress element	https://3dwarehouse.sketchup.com/embed/a8495c69-a705-41bb-a7d9-3a466a87730e
4. Representation of a body as a continuum of stress cubes; normal stress on a stress cube	https://3dwarehouse.sketchup.com/embed/9f5f875b-a2ca-48f7-bc19-a786214e87a2
5. Hooke's Law (the spring experiment)	https://3dwarehouse.sketchup.com/embed/2375e9ab-8bea-4e57-8dd0-ea42f6be52a2
6. Fixed-free bar subjected to axial tension	https://3dwarehouse.sketchup.com/embed/0a95ea86-cb13-4769-8c26-ac374464d431
7. Sign convention for planar shear stress	https://3dwarehouse.sketchup.com/embed/ecf7f7d3-b7bf-431c-8c96-d4a75ae608c8
8. Sign convention for all 3D normal and shear stresses	https://3dwarehouse.sketchup.com/embed/5292d06d-61f7-4f58-8f88-d157e8be9498
9. Poisson's Ratio	https://3dwarehouse.sketchup.com/embed/0ba7cd9d-5174-4206-bf2c-73e1ad008bc4
10. Axial deformation of a simple axial member	https://3dwarehouse.sketchup.com/embed/ea229348-2ef2-4e5e-9c48-d98d0a41e743
11. Axial deformation of a compound axial member	https://3dwarehouse.sketchup.com/embed/d6a98d25-f789-4200-824a-083ed3555be0
12. An unconstrained beam subjected to thermal effects	https://3dwarehouse.sketchup.com/embed/29e12487-f414-4b96-82f3-f732a0079c00
13. A spherical pressure vessel	https://3dwarehouse.sketchup.com/embed/655cb531-f2a4-4b1a-8d4b-41d68803aaa7
14. A cylindrical pressure vessel	https://3dwarehouse.sketchup.com/embed/bfa2aef5-f451-4da2-86cc-44cd7943266f
15. A composite steel and concrete (co-axial) column	https://app.sketchup.com/viewer/3dw?WarehouseModelId=faa0d090-ade4-464c-bcd2-e76e725b0176
16. A rigid beam supported by deformable (flexible) cables	https://3dwarehouse.sketchup.com/embed/f3a160dd-877a-4800-86b9-8f4c4a217275
17. Deformations that result from shear force and from bending moment	https://3dwarehouse.sketchup.com/embed/62d17a9f-8c81-4ac6-8d01-942b4423fa52
18. Centroid / center of area (checkerboard analogy)	https://app.sketchup.com/viewer/3dw?WarehouseModelId=e78c683a-bd5b-4a76-9d94-0ebd819daf05
19. Strong-axis bending vs. weak-axis bending of a beam	https://3dwarehouse.sketchup.com/embed/97404547-9c22-47b4-8be5-d74d3d088a20
20. Cantilever beam subjected to an applied moment (derivation of the flexure formula)	https://app.sketchup.com/viewer/3dw?WarehouseModelId=7711106b-2054-4d43-8cc6-7447b4945e55
21. Distribution of flexural stress on a cross-sectional plane for positive and negative bending	https://3dwarehouse.sketchup.com/embed/c93a7ae7-8f10-4eb0-b0b6-3d33cf180680
22. Derivation of the formula for transverse shear stress in a beam	https://3dwarehouse.sketchup.com/embed/6497c123-1137-47f8-a029-12a18ab0a723

23. A solid cylindrical shaft subjected to torsion	https://3dwarehouse.sketchup.com/embed/622b26e3-4986-4654-a9ba-d2a40b257b31
24. A hollow cylindrical shaft subjected to torsion	https://3dwarehouse.sketchup.com/embed/6515c011-97fc-4df1-b3f2-ee1be37d36ba
25. Comparison of a stocky column and slender column (both pin-pin)	https://3dwarehouse.sketchup.com/embed/184cc5e2-8434-4aef-9941-25e7d848632b
26. Pin-pin columns and bracing – small wood structure	https://3dwarehouse.sketchup.com/embed/23db4b67-4c0a-4c96-9fd5-698fa7dba9ff
27. Wood column supported by through-bolts	https://3dwarehouse.sketchup.com/embed/5b95c36e-6617-4794-a9a3-77c4270b8ae6
28. A wall-mounted shelf	https://3dwarehouse.sketchup.com/embed/1f662cd0-0d6c-4586-b22b-55f4c0a54703
29. Members susceptible to stress concentrations due to a hole, a notch, or a taper	https://3dwarehouse.sketchup.com/embed/bd2df354-c476-4099-90f6-02abe0980237
30. An eccentric compressive force (combined axial and flexural stress)	https://3dwarehouse.sketchup.com/embed/5ec6193e-d8c4-4482-be9f-6c52d231bc6e
31. Combined stress: an allen wrench in static equilibrium	https://3dwarehouse.sketchup.com/embed/9aa9171e-5a13-4f2a-9e62-80892a63518c
32. A C-clamp compresses a block of wood	https://3dwarehouse.sketchup.com/embed/a4cd32bb-e4b8-4ce6-ae47-38792c51e44d
33. A 3D bent pipe subjected to moments and forces	https://3dwarehouse.sketchup.com/embed/ab9c450e-95bc-4db7-aa45-0577dcde424c
34. Stress on an inclined plane	https://3dwarehouse.sketchup.com/embed/a3fd5081-1609-4124-86fd-b0442387613b
35. Stress transformation in 3D: rotation to principal planar stresses in xy, yz, and xz	https://3dwarehouse.sketchup.com/embed/689bcf8a-a71b-4ef9-b4b7-24998419d4df

Open Educational Resources (OER) and SketchUp software

There is growing momentum in higher education towards the use of Open Educational Resources (OERs): teaching and learning tools that are published in the public domain or under Creative Commons licenses that permit redistribution and reuse. They are often, but not always, zero cost materials [20].

The *Seeing Structures* 3D models were created in SketchUp (by Trimble). This software package has similar functionality and power as other 3D-modelers (AutoCAD, SolidWorks, etc.) but has been designed in an accessible way that may be mastered by primary and secondary students. SketchUp's functionality is beneficial to architects, engineers, makers, and product designers.

SketchUp has two different interfaces. SketchUp for Web is open-source and freely available. There is no download, it is zero cost, it is used in a browser, and has the functionality required to create models similar in size and scope to the ones depicted in this paper. There are also professional, paid versions (SketchUp Pro, SketchUp Studio) for users that want to use advanced tools and features.

The *Seeing Structures* visualizations have been uploaded to SketchUp's 3D Warehouse, a place to share and download models. All 3D Warehouse users accept terms and conditions that place uploaded models in the public domain. The models may then be downloaded and used by the public. Users may modify another user's model and reshare it as a new model. According to the 3D Warehouse terms and conditions, this is a perfectly acceptable use of the technology [21].

The SketchUp file extension (.skp) is interoperable with other popular CAD software. A model that has been shared on the 3D Warehouse may be downloaded, exported to a compatible program, modified, and reshared as a new OER. Compared to HTML5, SketchUp appears to be an easier option for most engineering faculty interested in creating interactive visualizations.

While the scope of this paper is limited to engineering mechanics, the presentation of OER and SketchUp is suitable and transferrable to other engineering fields, such as geotechnical engineering, construction engineering, transportation engineering, architectural engineering, environmental engineering, and more.

Use of OER in engineering mechanics courses

A 2020 study by Moore and Reinsfelder revealed that the majority of engineering mechanics courses use traditional textbooks. Barriers to OER adoption in engineering courses include the prevalence of the coordinated course approach (i.e. most instructors do not have the freedom to choose a text) and a lack of time to find OERs and check them for accuracy. The same study recommends that OER developers "work to create quality, peer-reviewed content with rich sets of worked example problems" and that of all of the barriers to increasing the use of OER in engineering mechanics courses, this is the most critical barrier to overcome [7].

Table 2. Known (recent) OERs for engineering mechanics courses

	URL	Lectures and Problem Sets	Interactive visualizations	Principal Field(s)
MecMovies	https://web.mst.edu/~mecmovie/ (obsolete)	Yes	Yes	Mechanics of Materials
Engineering Statics	https://oli.cmu.edu/courses/engineering-statics/	Yes	Yes	Statics
Mechanics Map Open Textbook Project	http://mechanicsmap.psu.edu	Yes	No	Statics and Dynamics
Purdue Mechanics Freeform Classroom	https://www.purdue.edu/freeform/statics/visualizing-mechanics/	Yes	No	Statics, Dynamics, Mechanics of Materials
Seeing Structures	https://people.mines.edu/sreynold/smr/seeing-structures/	No	Yes	Mechanics of Materials

Assessment of the *Seeing Structures* CAD Visualizations

Prior to the remote offering of Mechanics of Materials, exams were delivered in-person. Exam problems were presented to students on hard copies. In the traditional exam format, the instructor decides what information to show on the page. Problem presentation can be two- or three-dimensional. Extraneous information (sometimes called "distractors") can be included or excluded from the problem statement as part of the design of the assessment instrument.

In the remote offering of Mechanics of Materials, university policy did not permit in-person exams. Additionally, the enrollment included international students living in a variety of time zones. To accommodate these constraints, exams were reimagined into a 24-hour "take-home" format. The new format facilitated longer questions that were more complex than feasible in the in-person modality. In lieu of 2D or 3D drawings, students were provided with a link to an interactive, multi-view 3D model (Figures 16, 17, and 18). The exam models were uploaded to the 3D Warehouse in advance of the exam, but kept private until the exam began.

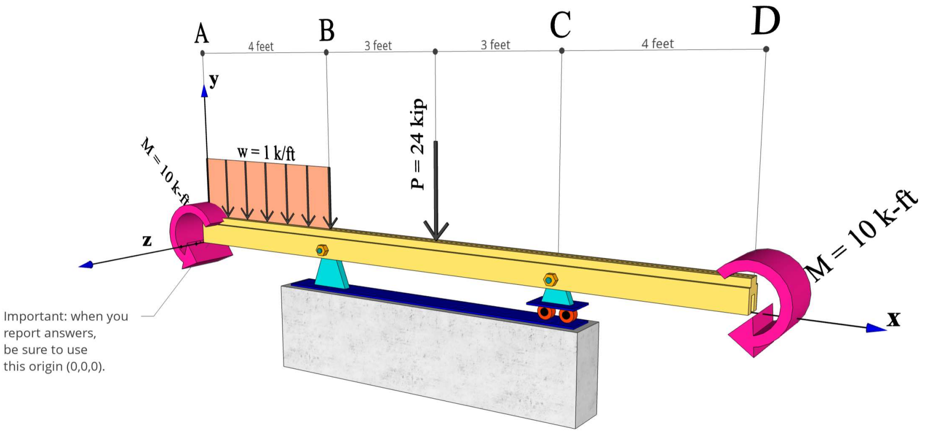


Figure 16. Sample exam question (assessment of student mastery of flexural stress)

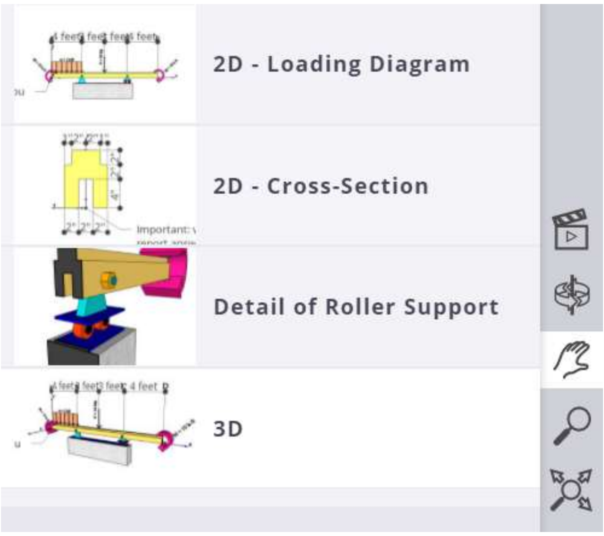


Figure 17. Menu of views provided to students

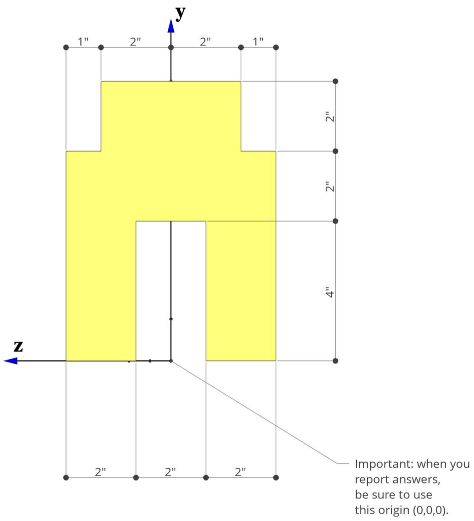


Figure 18. Cross-sectional view of member

Student mastery of learning outcomes cannot be quantitatively compared by tabulating exam results from the remote semester against those from prior face-to-face semesters. Too many variables had changed, including differences between teaching and learning online; between take-home and in-person exams; and consideration of the elevated levels of student stress and anxiety related to the many effects of the COVID-19 pandemic.

In lieu of quantitative assessment, qualitative assessment of the project may aid others who wish to pursue similar ideas as presented here. One successful aspect of the experiment is that the 3D model provides a more authentic emulation of real-world engineering practice. Students may peruse the views and orbit the model in 3D to understand the nature of the problem. This type of engagement, inquiry, and discovery is typically not possible in traditional paper exams.

Additionally, by modeling the context in 3D, the exam designer is forced to fully develop the problem in a way that is not typically done for an on-paper exam. For example, consider the unusual cross-section. The unconventional shape was strategically chosen to limit students' ability to use online moment of inertia solvers during the take-home exam. However, the unusual shape of the cross-section necessitated a custom-designed roller support (Figures 16, 17).

Through the act of grading the take-home exam, it became clear that student misunderstandings of key learning outcomes were more exposed in the new format compared to prior grading experiences of traditional exams. Anecdotally, there was more scatter in student problem-solving approaches. This could be attributed, in part, to the multi-step nature of the take-home exam: compute the location of the centroid, then the moment of inertia, then the moment diagram, and finally the flexural stresses. This experiment in exam design was a success in that it provided the instructor with a tool to assess student learning in a more authentic way.

The biggest take-away from the experiment is that there is inherent bias towards the correct solution method in the way a problem is presented on a traditional paper exam. By providing a more neutral 3D representation of the exact same problem, student problem-solving approaches vary significantly. The new technique exposes student misunderstandings that may not be discernible in traditional paper exams. A heightened awareness of incorrect problem-solving approaches will lead to improvements in course design and exam design in future iterations.

Student feedback on the *Seeing Structures* CAD Visualizations

Student feedback on the effectiveness and usefulness of the *Seeing Structures* project was solicited from students through an anonymous survey deployed after the conclusion of the semester. The response rate was 41% (37 of 90) and the feedback was universally positive. This survey serves as a qualitative assessment of the project's potential. The survey prompt and selected responses follow.

Survey prompt: In Fall 2020, I devoted some time to developing CAD visualizations for Mechanics of Materials. They are a work in progress, but are slowly coming along. I am now proposing a project in which I would expand the library of models as a common resource for Statics, Mechanics of Materials, and other engineering mechanics courses. Any feedback on this idea?

Sample survey responses:

- These models are a huge resource and learning tool. I would think that open access to this material would be a value-added resource to the Mines community. I can say from first-hand experience that using these models helped me achieve success in Mechanics of Materials.

- These models really help for out-of-the-classroom activities like HW and studying. Moreover, while in lecture, either remote or in person, it helps to have something to see/touch to understand the concepts, but also to see gaps in our own understanding.

- The CAD models in this class … were extremely helpful for being able to visualize and understand the material. As Statics is one of the first classes in the CEEN route that requires spatial visualization I think these models could be an imperative help to students taking any course, but especially Statics. They were extremely helpful for me in MechEMat and couldn't imagine taking a course like that without them.

- The models really helped when learning the material in your course and they should be accessible to as many students as possible. The models added a 3D aspect to the lecture notes and worked very well during lecture as most students now take notes on a tablet or a program like OneNote and could easily reference the models when studying the material. Even when Mines can safely shift to normal in-person learning after COVID, the models will be a useful tool for students to look back to when completing problem sets or studying for exams.

Diversity, Access, and Equity

Several aspects of the *Seeing Structures* project relate to supporting diversity, inclusion, and equity. First, the CAD visualizations have been placed in the public domain as zero-cost OERs. This increases equitable access to students in any course that adopts these visualizations in lieu of published textbooks or other learning materials that bear a cost.

Many of the *Seeing Structures* visualizations include human figures for scale. Other models use cats or dogs for the same purpose. Most of these scale figures were downloaded from the 3D Warehouse. The earliest models used scale figures that were overrepresented, predominantly white and male. As the project proceeded, a concerted effort was made to search the 3D Warehouse to better represent a diversity of gender, racial, and cultural identities. The use of scale figures also makes the size of the represented objects immediately apparent to all students, regardless if they are American students with cultural knowledge of U.S. Customary Units or international students with cultural knowledge of SI Units.

In traditional engineering mechanics classrooms, instructors may sketch complex geometry as board notes. Some students with disabilities, most notably dysgraphia, are not able to duplicate those board drawings. Universal course design principles dictate that courses can and should be designed as flexibly as possible to accommodate students. The CAD visualizations may aid those students who are uncomfortable with drawing and let them focus on the underlying concepts and not their individual abilities with respect to spatial analysis and technical drawings.

Finally, there is a known experience gap in engineering mechanics courses. It is not related to students' math aptitude, but to the practical knowledge some students have accrued related to nuts, bolts, nails, screws, welds, etc. Not all students have experienced the act of building or fixing things at home or in school. The CAD visualizations demystify the jargon for students who may have less practical building experience and provide a more equitable learning experience for all.

Recommendations for others who wish to undertake similar projects

The first-generation of the *Seeing Structures* repository of CAD visualizations was completed during Fall 2020. The work was not pre-planned and was completed without funding, collaboration, or external support. It was simply a teaching innovation in one class at one institution that was intended to support student learning during a pandemic.

Other faculty that are motivated to undertake similar projects are encouraged to start small. SketchUp is a user-friendly program that is accessible to any engineering faculty, especially those with CAD experience in other programs. Student hourly workers or graduate research assistants may provide valuable support to faculty interested in this technology.

The author also recommends taking time to plan models that can illustrate multiple concepts. For example, one good quality model could illustrate different concepts at different points in the course: static equilibrium, internal forces, stress analysis, column buckling, stress transformation, etc. Currently, each model in the *Seeing Structures* repository targets one primary concept.

Faculty that wish to undertake similar projects are also encouraged to learn about OER and the Creative Commons licenses, so that work can continue to be shared and best practices can be established.

Conclusions and Future Work

The *Seeing Structures* project began as a teaching innovation in a single class. The project has shown that modern engineering instructional materials can be designed to explain abstract concepts (e.g. stress, strain) concurrently with the practical reality of engineering (e.g. connectors and connections). Assessment is ongoing, but preliminary student feedback indicates that the project has potential to be impactful across the sequence of engineering mechanics courses.

Over time, the *Seeing Structures* repository of interactive CAD models is envisioned as part of a broader OER initiative for engineering mechanics courses. Benefits of the first generation of the *Seeing Structures* interactive CAD visualizations include their use as teaching tools for faculty, learning tools for students, and as OER that may be equitably shared across higher education. While specifically created in response to online teaching necessitated by the COVID-19 pandemic, the models do have applicability for both online and in-person teaching modes.

Future work on the project includes outreach to other faculty passionate about OERs for engineering mechanics, an expansion of the library of models to include concepts relevant to engineering statics and upper-level structural engineering mechanics courses, and exploration of animation capabilities that provide enhanced user interactivity.

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