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Work-In-Progress: Further Work on a Learning Tool to Enhance Understanding of Stress States and Mohr's Circle

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Abstract

Mohr's circle is a fundamental concept discussed in introductory Mechanics of Materials courses to help visualize and analyze stress and strain in materials. Despite its importance, students often struggle with its abstract nature and its application to real-world stress states in physically loaded structures. To bridge this gap and enhance student understanding, a MATLAB app and a handheld tool are currently under development designed to facilitate experiential learning of stress transformations and Mohr's circle. When linked together, this tool will provide students with real-time feedback on the stress state of physically loaded structures, enabling them to explore stress transformations in axial, torsional, and flexural loading scenarios.

This paper presents updates on the development of the app, assessment for the app, and fabrication of the handheld tool. The MATLAB app has been refined to enhance user experience and understanding, offering clearer instructional guidance and warnings for buckling and failure. The paper discusses design of an assessment to evaluate the app's effectiveness in improving student comprehension of stress transformations and Mohr's circle. For the assessment, multiple choice questions using three levels of abstraction are used to measure students' level of knowledge acquisition. Additionally, the paper outlines updates to the handheld tool design, focusing on cost reduction and simplified manufacturing. The paper reports the manufacturing process and costs, along with details of the electronic and software configurations required to link the handheld tool with the MATLAB app. Future work will involve executing a study to collect and analyze data on the app's effectiveness and finalizing fabrication of the tool, ensuring readiness for the next phase of research.

Introduction

Mechanics of Materials (MoM) is the study of how stresses and strains generated by the application of external forces affect structural members. MoM concepts consider directly observable phenomena (e.g., application of forces on structural members, deformation of materials, and fracture) and abstract phenomena (e.g., development of stress and strains, material properties, and energy transfer). However, integrating the directly observable and abstract is challenging as students develop their emerging MoM conceptual understandings [1,2]. Traditionally, theory-based MoM courses opt to instruct by predominately using a formalism first (FF) instructional approach [3]. Formalisms include the disciplinary language used within the MoM course, equations to quantify stresses and strains under various loading scenarios, and the procedures required to make accurate calculations. The FF paradigm of education exposes students to concepts by first teaching these formalisms, which can be challenging for students as it provides limited opportunities for directly observable and personal experiences during instruction [4].

For example, undergraduate engineering students are commonly introduced to Mohr's Circle in their theory-based MoM course. Mohr's Circle is a formal and graphical analytical tool for exploring stress transformations. It abridges the process of reorienting a given planar section of material to obtain principal stresses and strains at new orientations without extensive calculations [5]. Although Mohr's Circle adds simplicity in analyzing stress states, many students find this graphical approach abstract and struggle to apply relationships of stress states to physically loaded structures [6]. Therefore, there is a need to develop instructional activities that bridge between the formal, graphical procedure of using Mohr's Circle and alternative conceptual learning frameworks that ground students' understandings of the relationships between stress states on physically loaded structures. The proposed learning tool addresses this need by incorporating the principles of grounded and embodied learning [7]. Through this tool, students will directly apply forces to structural members, gaining a tangible sense of the forces required to deform them, while simultaneously linking these physical experiences to stresses and the abstract graphical procedure of Mohr's Circle.

Theoretical Background

At the epicenter of engineering education is the intent to couple the abstract knowledge from physics, mathematics, and theory to real-world phenomena. John Dewey was credited as the founder of experiential learning, an educational theory advocating for direct experiences alongside topics being studied, rather than simply discussing and considering them [8]. Following Dewey, Jerome Bruner disparaged the prevailing educational paradigm of rote memorization as a strategy for knowledge acquisition, contending that procedural and declarative knowledge limited the development of robust understandings [9]. Bruner argued the importance of physical interactivity to ground new ideas and formalisms that support generalization and abstraction [10]. *Progressive formalization*, or *concreteness fading*, provides a developmental pathway from concrete experiences to more idealized and abstract representations central in STEM education [3,11, 12]. Progressive formalization has extensive empirical support. As an example, Goldstone & Son [11] found that student's ability to learn and then transfer their understandings of the concept was best in the concreteness fading condition when the initial simulation elements were concrete and then became idealized. The concreteness fading condition not only outperformed the other conditions in their study but also showed the most reduction in error on a follow-up assessment.

Undergirding the affordances of progressive formalization is that perception fundamentally *grounds* our understandings of real-world phenomena. Barsalou [13] contended that cognition is grounded by perception, action, and introspection situated by the affordances in an environment. Formalisms can be grounded by real-world referents via mapping of personal experiences onto abstractions by incorporating body-based, or *embodied*, resources into the learning environment giving rise to a new paradigm of instruction—*ground and embodied learning* [7, 14]. In-line with progressive formalization, grounded and embodied learning activities expose students to new concepts by exploring them through lived experiences prior to the application of formalisms. As an example, Mohr's Circle can be a foundational tool for MoM students developing their conceptual understandings by integrating directly observable phenomena (e.g., students directly applying forces) to visualize the unobservable stresses developed in a structural member (e.g., abstract phenomena). As students directly apply various forces, they can develop a grounded, sensorimotor understanding of the magnitude of force required to deform a material as the internal stress of a member increases. The newly grounded knowledge can then be applied later as students problem-solve and generate Mohr's Circles. We contend that the inclusion of real-world referents through the use of a handheld, physical manipulative device can ground students emerging conceptual understandings of stresses and strains in route to garnering expertise for the concepts of stress transformations and Mohr's Circle.

Updates to the App

A MATLAB GUI has been developed through MathWorks MATLAB App Designer [15]. The app features a tab-based navigation system that provides options for 2D and 3D visualizations of Mohr's circle based on user-defined stress states for two- and three-dimensional differential elements. It also includes options for cuboid, cylinder, and hollow cylinder geometries. By enabling users to input loads on various geometries and visually explore the resulting stress states, the app aims to help students connect the abstract graphical representation of Mohr's circle to the stress states of loaded structures. Additional details about the app's features and functionality are provided in previous work [16].

Following informal feedback from initial users, the MATLAB app has been refined to enhance both usability and conceptual clarity. Instructional guidance is provided at the click of a button to help users navigate the app effectively. The input interface uses fill-in boxes, allowing students to experiment with a range of geometries and loads in the cuboid, cylinder, and hollow cylinder tab selections. Additionally, users choose from a selection of materials, including steel, aluminum, titanium, and copper. To address cases where user inputs exceed material strengths or buckling loads, warning messages have been added to alert users to excessive stress and buckling failure, promoting a deeper understanding of material limitations.

Assessment Plans for the App

In recognizing the stark differences in how novices and experts approach and represent problem solutions and the various stages of acquiring expertise, an assessment that tracks students' emerging conceptualizations of stress transformations and Mohr's Circle has been developed to adequately assess the effectiveness of the MATLAB application on learning outcomes [17, 18]. For the assessment, multiple choice questions using three *levels of abstraction* including less-abstract, more-abstract, and fully-abstract are used to measure students' level of knowledge acquisition between three stages: novice, competent, and expert [18]. The level of abstraction is defined as the degree of complexity of the concept of thought [19]. That is, the more information a problem includes that must be reasoned through and about, the more abstracted the problem becomes. For example, a less-abstract problem requires students to reason only about uniaxial stresses whereas a more-abstract problem involves students considering multiple stresses acting on material in different planes, and a fully-abstract problem challenges students to reason about the effects of stresses in multiple planes on different geometric shapes.

The level of abstraction and knowledge acquisition were mapped onto learning objectives developed for the unit of stress transformations and Mohr's Circle. Learning objectives (LO) for this unit, and pertaining only to the MATLAB application, include:

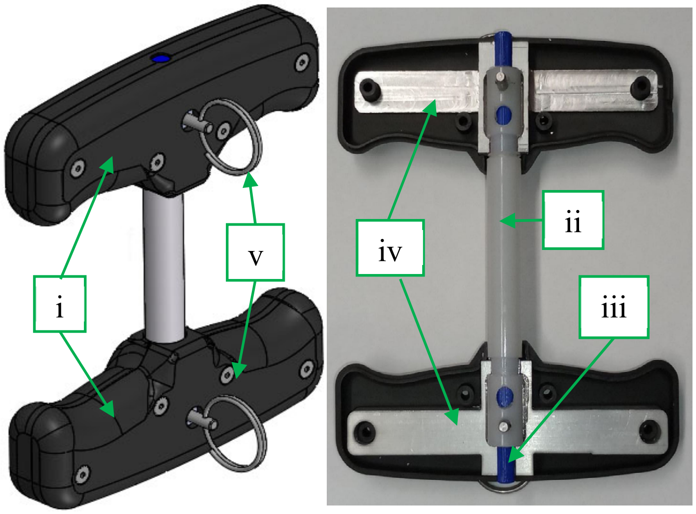
(LO1) identify principal stresses, principal angle, and maximum shear stress
(LO2) identify stress variation with transformation angle
(LO3) identify variation in principle stress and maximum shear stress as specified location change on the structure, the magnitude of an applied load varies, and dimensions and material of the structure changes, and
(LO4) recognize distinguishing features among Mohr's Circle for uniaxial tension and compression and pure torsion.

For example, a less-abstract question for LO1 may ask students to reason about a Mohr's Circle for a uniaxial compressive load, a novice concept. The question prompts students to identify the directionality of the uniaxial stress on an element that corresponds with a provided Mohr's Circle. In essence, if the Mohr's Circle is on the left-hand side of the shear stress axis, what is the directionality of the stresses acting on the stress element? In this less-abstract question, students are solely reasoning about the directionality of a uniaxial stress that produces a provided Mohr's Circle. This question resides within the novice stage as it pertains to only to factual information about what uniaxial stresses produce which Mohr's Circles. Of course, this problem can become more abstract by including more information such as multiple stresses acting over the stress element, or similar stresses acting on different geometries.

The purpose of this assessment is to track the level of knowledge acquired by students while exploring stress transformations and Mohr's Circle in a MATLAB application. To do this, we have coupled the level of abstraction with the level of knowledge acquisition per learning outcome. In doing so, we can establish a trajectory of students' level of acquired knowledge between pre- and post-assessment formats at the individual level. Aggregating data from the individual level can provide necessary insights into the effectiveness of the MATLAB application for student learning, such as the effectiveness to promote students' level of acquired knowledge. Using Bayesian Linear Regression modeling, the research team can establish an initial exploratory model to be updated with future collected data from other cohorts. Effect sizes output from the model will then be used within a cost-effectiveness analysis to determine the cost to achieve a unit increase in effect, a necessary metric to inform stakeholders and decision-makers of the cost to improve the instruction for the concepts of stress transformation and Mohr's Circle.

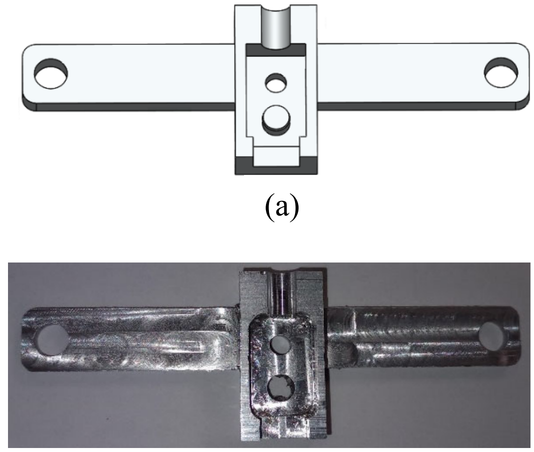
Design and Manufacturing of the Handheld Tool

The app alone serves as a tool for exploring stress transformations and understanding Mohr's circle, guiding students to relate these foundational concepts to real-world loaded structures. To enhance this connection and provide a more immersive learning experience, a handheld device has been designed and fabrication is in progress. The handheld tool will translate physical deformations of a sample material into inputs in the app. Inspired by the device created by Moller and Mokaddem [6], the handheld tool will capture axial, torsional, and bending deformations each with a rosette of strain gauges. The strain gauge signals will be amplified by a microcontroller housed in one of the device handles and passed to the app running on a PC via USB. The following outlines updates from the original design proposed in previous work [16] aimed at reducing costs and simplifying manufacturing processes to facilitate student production. It also provides details on the electronic and software configurations necessary to integrate the tool with the app.



(a) (b)

Figure 1. SolidWorks rendering of the handheld tool (a), and exposed internal features of manufactured parts (b).



(a)

(b)

Figure 2. SolidWorks rendering of the internal structure with dowel pin (a) and manufactured internal structure (b).

Table 1. Outline of components and design updates for the handheld tool.

Component	Label	Qty	Design Updates
Handle housing	i	4	• Updated to match the redesigned internal structure • Reduced variable filets to minimize used material
Nylon sample material	ii	1	• Updated to match the redesigned internal structure
Carbon steel central rod	iii	1	• No modifications.
Internal structure with keyed features	iv	4	• Modified internal structure to a rectangular shape and improved design for easier machining • Removed a keyed feature on inner handle and installed a dowel pin as shown in Figure 2(a)
Retaining pins	v	2	• No modifications.

A SolidWorks rendering of the handheld tool design is shown in Figure 1(a) alongside the manufactured components of the handheld tool in Figure 1(b). Design updates from the original design proposal are outlined in Table 1. The updates primarily focused on simplifying the internal structure and keyed features to streamline manufacturing as shown in Figure 2. This included a redesign of the internal structures as well as removing one of the original keyed features and replacing it with a dowel pin as shown in Figure 2(a). These design changes reduced machining complexity and associated costs, while also making the tool feasible for student fabrication.

Regarding manufacturing, the housing handles were 3D printed using Fused Deposition Modeling (FDM) with Polylactic Acid (PLA) filament an 80% infill. The screw holes were tapped as a secondary operation. The nylon test material was supplied as rod stock and bored out on a collet lathe before the keyed features were machined on a vertical mill. The blank for the internal structure was manufactured using a waterjet, and additional holes, channels, and keyed features were added through vertical milling. To complete the assembly, the dowel pins were installed.

Component and Manufacturing Costs of the Handheld Tool

The total cost of the handheld tool was approximately $172, which includes around $95 for the components and $77 for manufacturing. A detailed breakdown of these costs is provided in Table 2. Manufacturing with the mill and lathe was carried out in the university shop by a trained undergraduate engineering student as part of a credit-bearing project. 3D printing and waterjet cutting were performed in the university makerspace.

Table 2. Cost of components and manufacturing.

	Qty	**Cost**	**Total**
Component		($)	($)
Central steel shaft	1	7.52	7.52
Nylon sample material	1	0.77	0.77
Material for internal structure	4	1.51	6.04
Handle housing	4	1.25	5.00
Fasteners	8	0.43	3.44
Retaining pin	2	4.30	8.60
Microcontroller board	1	8.95	8.95
Amplifier	3	8.16	24.48
Strain gauge	12	2.50	30.00
			94.80
Manufacturing			
3D Printing – Handle housing	4	1.65	6.60
Waterjet – Internal structure	4	17.54	70.15
			76.75
		Total Cost ($)	**171.55**

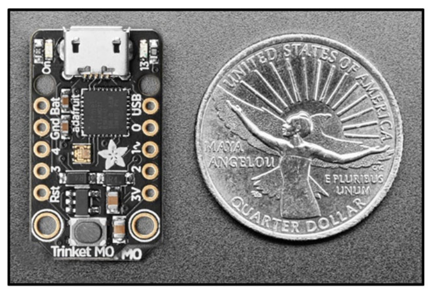


Figure 3. Adafruit Trinket M0 (with quarter for scale).

Details of Electronic Configuration

Electronically, the handheld tool will be controlled and powered by an Adafruit Trinket M0 microcontroller board utilizing an Atmel ATSAMD21 microprocessor as shown in Figure 3. This board, along with three Analog Devices AD627 instrumentation amplifiers, will be housed inside one of the handles of the handheld tool. Power to the microcontroller board will be provided via an onboard MicroUSB port connected to the host computer. The M0 will send 3.3V to each of three Wheatstone bridges, comprised of four Micro Measurements 240UZA-series strain gauges, and to each of the three AD627 amps. Each Wheatstone bridge will capture deformations in one of three modes: axial, torsional, and flexural bending. The analog signals from each bridge will first route to the AD627's to be amplified, then pass to the M0 to become digitized by the microprocessor, and finally sent to the host computer via the same MicroUSB cable providing power. Figure 4 illustrates the Printed Circuit Board (PCB) schematic.

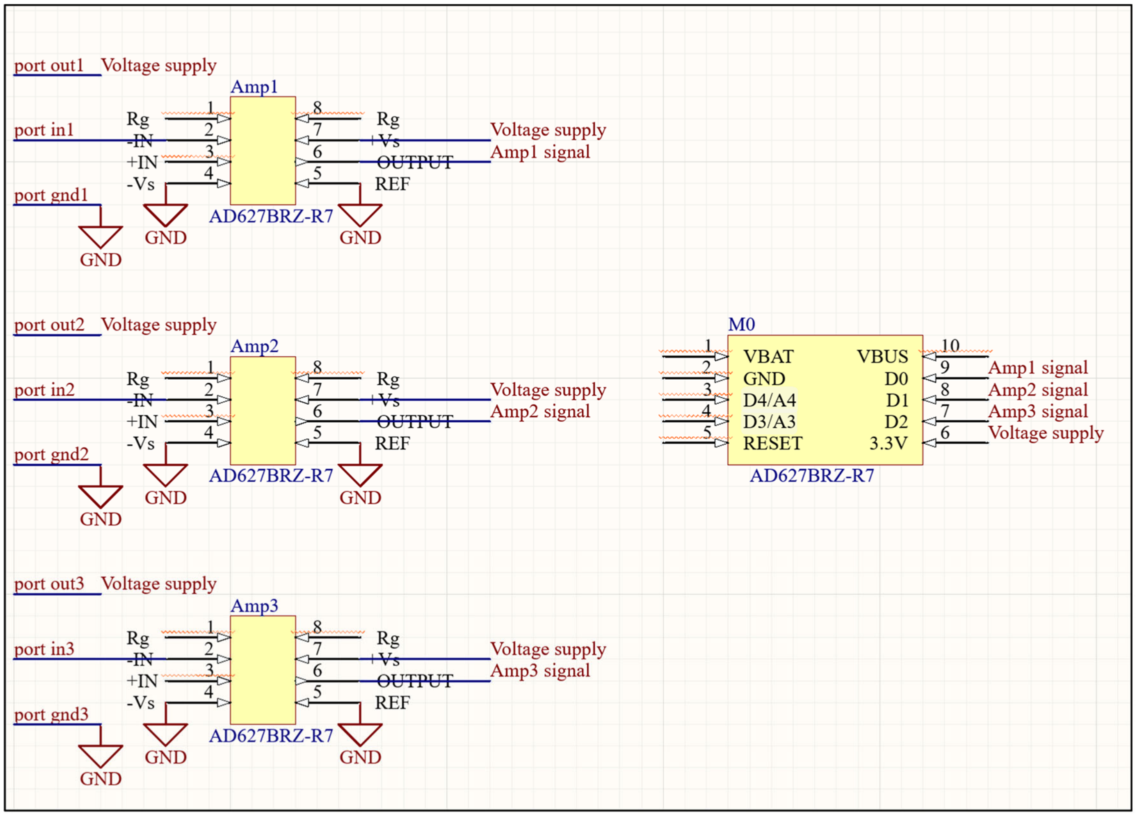


Figure 4. PCB Schematic.

Future Work

This paper outlines the ongoing development of a learning tool designed to improve student understanding of stress states and Mohr's circle in an introductory Mechanics of Materials course. Recent efforts have focused on updating the MATLAB app to enhance user experience, developing pre- and post-assessments for a study measuring the app's effectiveness, and fabricating a handheld tool that enables experiential learning when paired with the app.

Future work includes conducting a study to evaluate effectiveness, collecting and analyzing the data, and using the results to guide further improvements to the app. Additionally, the fabrication of the handheld tool will be completed, including mounting strain gauges, installing electronics, and writing MATLAB code to convert raw data into stress values that students can visualize and explore through the app. This research will lay the foundation for further studies aimed at evaluating and refining the handheld tool in conjunction with the app. These subsequent investigations will focus on optimizing the tool's design, enhancing integration with the app, and exploring its impact on student engagement and learning outcomes in greater depth.

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