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Assessing ABET SO6 through Innovative Labs in Solid Mechanics: A comprehensive guide for Mechanical Engineering Instructors

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Work in Progress: Assessing ABET SO6 through Innovative Labs in Solid Mechanics: A comprehensive guide for Mechanical Engineering Instructors

Abstract

During ABET Assessment Cycle 2 (Fall 2023-Summer 2024) Department of Mechanical Engineering at Wentworth Institute of Technology (WIT), unanimously included a sophomore course, Mechanics of Materials, to be assessed for Student Outcome 6 (SO6) starting from Fall 2024 (September-December) semester. To assess this outcome, innovative and non-traditional labs were developed with a focus on solid mechanics where hands-on experiments help bridge the gap between theory, numerical analysis, simulations and real-world applications. The traditional lab exercises at majority of undergraduate engineering colleges (including ours) include compression, tension (flat and threaded), double shear, and torsion (circular and non-circular specimens). In this paper we have identified 6 different labs 1) Stress Concentration Analysis Around a Circular Hole, 2) Testing of Riveted Connections, 3) Beam Deflection, 4) Tensile Testing at Extreme Temperatures, 5) Buckling of Slender Columns and 6) Thermal Stress in Bimetallic Strips to assess SO6. The assessment data from Testing of Riveted Connections module revealed that a scaffolding approach, combined with targeted instructor intervention, is necessary to strengthen students' ability to develop new experiments and build students' confidence in tackling open-ended design problems. This paper will serve as a comprehensive resource for mechanical engineering instructors, providing not only detailed lab modules, objectives, procedures, outcomes, and challenges, but also optimized variables for experiments, troubleshooting methodologies, and references, and other resources.

1. Introduction

ABET, across engineering schools, ensures that undergraduate engineering programs meet quality standards critical to preparing graduates for professional practice. Student Outcome 6 (SO6) emphasizes an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions [1]. While there are several other courses in the mechanical engineering curriculum such as thermodynamics, heat transfer, and senior capstone design where SO6 can be assessed, those courses at WIT are reserved to assess other outcomes [2].

Conventional lab exercises in Mechanics of Materials focus on compression, tension, shear and torsion. These experiments use standard universal testing machines (UTM) like Instron, MTS, and Tinius Olsen machines to analyze material properties, stress, and strain. While these traditional lab assignments provide in depth knowledge of normal and shear stress, strain, torque, angle of twist and other mechanical properties of materials; for SO6, we need labs that challenge students to integrate theoretical analysis, experimentation, and simulation, to further deepen their grasp of material behaviors and structural design by designing their own lab with targeted instructor supervision [3]. Faculty members at WIT have unanimously recognized Mechanics of Materials as a potential course where SO6 can be assessed. At WIT in a 15 weeklong semester, we typically cover the following labs in mechanics of materials class:

1. Review of Engineering Mechanics (Statics)
2. Compression Test
3. Tension Test (With and without extensometer)
4. Double Shear
5. Beam Deflection
6. Torsion (Circular and noncircular specimens)
7. Two labs with SOLIDWORKS Simulation (tension and stress concentration)[4]

Common practices across several engineering schools are to provide students with corresponding lab manuals and demonstrate each experiment along with data collection and analysis techniques making it rather challenging to assess whether students could develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions on their own[5], [6].

We believe, to address SO6, mechanics of materials labs must shift beyond predefined protocols and challenge students to integrate theoretical analysis, numerical simulations, and hands-on experimentation. This approach not only aligns with the SO6 objectives but also provides students with critical skills for engineering practice. In this paper, we are proposing 6 different labs that can be used as a guiding tool for instructors to readily adapt if a similar course at their institution is also chosen to assess SO6. This paper also introduces corresponding lab modules and assessment rubrics designed to meet SO6 requirements by facilitating a deeper integration of theoretical knowledge, experimentation, and simulation. Proposed lab modules encourage students to design and conduct experiments with targeted instructor supervision, preparing them for the complex and rather ambiguous real-world engineering challenges.

2. Methodology

2.1 Objectives and Expectations:

Although the choice of Mechanics of Material as a course to assess SO6 at WIT may have been unanimous, the challenge lies in preparing students for an undertaking as big as designing their own labs with targeted instructor supervision. While this is not an easy task we intend to achieve it by progressively guiding students toward independent experiment design strategies through pre-lab activities, additional theoretical discussion, targeted instructor interventions to verify students' thought processes, and peer collaboration. Students should be provided with as much relevant information as possible to ensure that they are not thwarted by the lack of understanding. Given the multitude of resources available, students are consistently encouraged to explore beyond the material provided to determine how a certain experiments module can be developed and what results are to be expected. Additionally, it is recommended that instructors offer relevant calculation, simulation, and analytical tools as a supplementary material to help students prepare students for a challenge of this magnitude.

2.2 Development of Lab Modules

Based on the topics that are typically covered in the mechanics of material class across undergraduate engineering institutions we have identified six innovative lab modules. Of those 6 lab modules, only one, Testing of Riveted Connections, is fully developed, and designed to integrate theoretical, experimental, simulation, and design components to assess students' critical thinking and problem-solving skills. This lab was assessed for SO6 in Fall 2024, and we are planning to have a separate lab to be assessed in the Spring 2025 semester. A brief description of the proposed labs and other relevant information is provided in **Table 1**.

Table 1: Description of 6 different Lab Modules considered to be assessed for SO6

Number	Lab Module	Testing Machine	Supporting Equipment	Approximate Duration	Assessment Status
1	Stress Concentration Analysis Around a Circular Hole Lab Module	Universal Testing Machine (UTM) such as Instron, MTS, Tinius Olsen	Strain Gauges, Digital Image Correlation (DIC)	Approximately 2 to 3 weeks toward the end of the semester or quarter	In process
2	Testing of Riveted Connections Lab Module	UTM	Same as standard Tensile Test		Completed in Fall 2024
3	Beam Deflection Lab Module	Simply supported beam apparatus	Dial Gauges and Weights		To be assessed in Spring 2025
4	Tensile Testing at Extreme Temperatures Lab Module	UTM with extreme Environmental Chamber	Furnace/Cryogenic System, Thermocouples		In Process
5	Buckling of Slender Columns Lab Module	Compression Testing Machine; UTM	Dial Gauges, Customized Fixtures		In Process
6	Thermal Stress in Bimetallic Strips Lab Module	Hot plate or Oven	Thermocouples, Dial Gauges		In Process

Based on our findings and plans to develop these lab modules for SO6 assessment, we have created a brief description of each module in the following sections. Instructors are encouraged to use or disregard any part of it to implement these modules at their institution.

2.1.1 Stress Concentration Analysis Around a Circular Hole (In Process)

Objective: To investigate the effect of stress concentration around a circular hole in a flat plate subjected to uniaxial tension, validate analytical predictions, and compare experimental data with numerical simulations, if possible [3], [7].

Suggested Procedure:

- Students can either manufacture flat plate specimens made of aluminum, steel or brass if they are trained on turning and milling machines or instructors can provide students with a flat plate or varying thickness of each material containing a central circular hole of varying diameters.

- Strain gauges are affixed around the perimeter of the hole at specific angular locations (preferably 0°, 45° and 90° to measure localized stress and strain under loading [8]. Students are also encouraged to use DIC techniques if available[9].
- The specimens are mounted on a tensile testing machine, and uniaxial tension is applied incrementally.
- Strain data is collected at each load increment and used to calculate localized stress using Hooke's Law ($\sigma = E\varepsilon$)
- Theoretical stress concentration factors K_t are calculated using preestablished formulas provided in the mechanics of materials books [10]. It is important to note that to assess SO6 properly, we need to guide their experiment instead of providing them with the relevant formulas and overall procedures. Students are encouraged to conduct their own research and be creative in setting up their experiments.
- Numerical simulations using Finite Element Analysis (FEA) software are strongly encouraged and should be conducted to determine and validate the stress distribution around the hole. While it is not expected for students to have a background in FEA analysis, a great resource is available here [7].
- For assessment purposes students should compare experimental, theoretical, and simulation results and discuss any variations in terms of material behavior, experimental setup, simplifications, or assumptions in theoretical models and ultimately draw their conclusions.

Learning Outcomes: At the end of this lab module, students should be able to:

- Apply the concept of stress concentration and its significance in engineering structural design.
- Implement strain gauges or DIC for stress analysis and interpreting strain data.
- Predict stress concentration factors and check their validity through experimentation and simulation.
- Investigate the limitations of analytical and numerical methods in predicting stress behavior of real-world structures based on the theoretical values presented in the textbooks[10].

Challenges:

- Strain channels, adapters for strain gauges, and the gauges themselves are quite expensive [11], which limits the number of machines that can be used simultaneously. As a result, it might be beneficial to distribute the group more evenly towards the end or preferably in the middle of the semester allowing students ample time to develop and set up their own experiments.
- Based on the availability of the strain gauges, achieving precise placement and calibration of strain gauges for accurate stress measurements might be challenging for some students. Same applies to DIC methods as well.
- Refining and reiterating the finite element analysis in numerical simulations to accurately obtain stress gradients near the hole.

- Addressing variability in material properties or manufacturing imperfections in the specimens if these students are yet to take a course in materials science [12].

Instructors who wish to incorporate *Stress Concentration Analysis Around a Circular Hole module* as part of their SO6 assessment for the Mechanics of Materials course can refer to the recommended assessment rubric provided in **Table 2**.

Table 2: Recommended Assessment Rubric for Stress Concentration Analysis Around a Circular Hole

Performance Criteria	Unsatisfactory	Developing	Satisfactory	Exemplary
6a. Specimen Preparation and Strain Gauge Placement	The specimen is improperly prepared; strain gauges are not installed or are incorrectly positioned.	The specimen is partially prepared, and strain gauges are affixed but lack alignment with critical stress zones.	The specimen is properly prepared, and strain gauges are positioned accurately around the hole.	The specimen preparation is meticulous and strain gauge placement is precise and optimized for stress analysis.
6a. Application of Uniaxial Load	Load is applied inconsistently or outside the acceptable range and equipment is misused.	Applied load is inconsistent and alignment issues cause uneven stress distribution.	Load is applied correctly and evenly, and equipment is used appropriately.	Applied load is precise and uniform, and adjustments ensure accurate stress distribution.
6b. Data Recording and Interpretation	Data is incomplete, inconsistent, or incorrectly interpreted and key stress concentration metrics are missing.	Data is partially recorded and stress concentration values calculated but with errors or omissions.	Data is complete and stress concentration is calculated and compared with theoretical predictions.	Data is comprehensive and results are analyzed in depth, and discrepancies with theory are evaluated.
6c. Integration with FEA Results	No effort to simulate or compare experimental results with FEA.	Basic FEA conducted and comparison with experimental data lacks rigor or accuracy.	FEA results are accurate and variations with experimental data are identified and discussed.	Simulation results are highly accurate and detailed discussion of discrepancies and insights into modeling limitations.
6d. Engineering Judgment and Conclusions	Conclusions are missing or lack relevance to stress concentration behavior.	Conclusions are presented but lack support from experimental or simulation data.	Conclusions are logically derived from comparison of theoretical, experimental, and simulation results.	Conclusions demonstrate strong engineering judgment with critical evaluation of assumptions, data quality, and practical implications for stress analysis.

2.1.2 Testing of Riveted Connections (Implemented and Assessed in Fall 2024)

Objective: To evaluate the mechanical performance and failure modes of riveted joints under uniaxial tensile loading, and analyze the effect of rivet and plate material, number of rivets (rows and columns of rivets) spacing, plate width and thickness, and rivet diameter and arrangement on joint strength [13].

Suggested Procedure:

- Students either manufacture riveted joint specimens using similar (dissimilar might be too complex for undergraduate students) combinations of materials (aluminum, steel or brass) for both the sheets and rivets or can be provided with riveted specimens. We purchased riveted specimens through an internal Spark grant [14]. Rivet spacing, arrangement (single, double row) diameter and rivet material types of shear (single or double) are varied among specimens.
- Uniaxial tensile tests are performed with incremental loads and students report the type of failure.
- Load and displacement data are recorded until fracture, recording the maximum load or the load at which the joint fails and observing the failure mode. It is important to let students know about the types of failures ahead of time that can occur while testing uniaxially loaded riveted specimens. 1) Yield of gross section, 2) Fracture of the net section, 3) Shear rupture of rivets, 4) Yield of bearing area.
- Theoretical calculations of joint strength are performed using preestablished formulas for shear stresses and bearing stresses, highlighting the differences among σ_{gross}, $\sigma_{bearing}$, σ_{yield} and σ_{net}[14].
- Encourage students to conduct numerical simulations to model stress distribution and ultimately predict failure modes and have them compare experimental, theoretical, and simulated results to help them draw their conclusions based on the joint performance (maximum load or load at failure).
- Provide students with an open-ended design challenge requiring them to create a riveted joint. Students are then encouraged to determine the number of rows and columns and justify their choice of rivet diameter, considering material strength requirements. Students then discuss the implications of joint design and material selection in engineering applications, such as aircraft and bridge structures.

Learning Outcomes: At the end of this lab module, students should be able to:

- Apply the principles of riveted joint mechanics, including shear, yielding, rupture of rivets, and bearing stress.
- Predict and validate joint performance through theoretical calculations and numerical simulations.
- Develop engineering judgment for optimizing rivet design in open-ended and real-world engineering applications.

Challenges:

- Manufacturing riveted specimens with uniform spacing and alignment. If outsourced, the cost of the material could be high [15].
- Achieving accurate simulation of complex failure modes in numerical models.
- Skills required to accurately address the variability in rivet material properties and inconsistencies in rivet installation.

- Understanding and managing experimental setup constraints, such as alignment of tensile loads to minimize off axis stress; particularly in thick single shear riveted connections due to the introduction of off axis loads [3].

Instructors who wish to incorporate *Testing of Riveted Connections module* as part of their SO6 assessment for the Mechanics of Materials course can refer to the recommended assessment rubric provided in **Table 3**.

Table 3: Recommended Assessment Rubric for Testing of Riveted Connections

Performance Criteria	Unsatisfactory	Developing	Satisfactory	Exemplary
6a. Specimen Manufacturing	Riveted joints are improperly manufactured; dimensions or materials are inconsistent.	Riveted joints are manufactured but with minor inconsistencies in dimensions or material properties.	Riveted joints are correctly manufactured; dimensions and materials meet requirements.	Manufacturing is precise; all rivet parameters are carefully documented and optimized.
6b. Shear and Tensile Load Testing	Load testing is incomplete or incorrectly conducted; no failure modes are observed.	Load testing is conducted but with inconsistent application; failure modes are partially documented.	Load testing is accurate; failure modes are observed and recorded systematically.	Load testing is precise and comprehensive; failure modes are analyzed in detail.
6c. Joint Performance Analysis	No effort to analyze joint performance or compare results with theoretical predictions.	Basic analysis conducted; joint performance evaluated but with errors or incomplete data.	Joint performance analysis is accurate; results align with theoretical predictions.	Performance analysis is thorough and insightful; detailed evaluation of design implications included.
6d. Engineering Judgment and Conclusions	No conclusions are drawn; student shows no understanding of experiment implications.	Basic conclusions are presented but lack justification or connection to engineering principles.	Reasonable conclusions are drawn based on data and supported with relevant engineering reasoning.	Conclusions are thoughtful, well-supported, and demonstrate strong engineering judgment regarding experiment implications and improvements.

2.1.3 Beam Deflection (To be Assessed in Spring 2025)

Objective:

To investigate the deflection behavior of beams made of different materials (steel, brass, aluminum, and different types of woods) under various loading conditions, and compare experimental results with theoretical predictions based on beam deflection equations [10].

Suggested Procedure:

- Students measure and record the dimensions (length, width, height) of each beam to calculate the moment of inertia and span length.
- Elastic modulus for each material is obtained from literature[16].
- Beams set up could be in two configurations: simply supported and cantilever. At WIT it is only simply supported at the moment.
- Incremental point loads are hung at various locations along the beam.
- Deflections are measured at predefined locations along the beam using dial gauges.
- Theoretical deflections are calculated using standard beam deflection equations as provided in the literature[10]. For simply supported beam the deflection at a point located at a distance x from left can be written as $\delta = -\frac{Px}{48EI}(3L^2 - 4x^2)$; where P, L, E, I, and applied load, length, elastic modulus, and moment of inertia of the beam.
- Experimental data is compared with theoretical predictions to analyze the relationship between material properties $(P, L, E, and\ I)$ and deflection behavior (δ).
- Students discuss any variation in the deflection values, identifying potential sources of error such as support conditions or inaccuracies in measurements using dial gauges or vibrations.

Learning Outcomes: At the end of this lab module, students should be able to:

- Implement the relationship between material properties $(P, L, E, and\ I)$ and deflection behavior (δ).
- Develop skills in setting up and conduct beam deflection experiments and read deflections from the dial gauges.

Challenges:

- Making sure that students calculate the moment of inertia correctly. In our case all the beams are of rectangular or square cross section.
- Proper alignment of support between span length and incremental load application to minimize experimental error.
- Accurate measurement of small and large deflections, especially for stiffer and flexible materials like steel and wood(s) respectively.
- Addressing variability in material properties, particularly for natural materials like wood (various types).
- Trouble reading the value of deflection from a dial gauge.

Instructors who wish to incorporate *Beam Deflection module* as part of their SO6 assessment for the Mechanics of Materials course can refer to the recommended assessment rubric provided in **Table 4**.

Table 4: Recommended Assessment Rubric for Beam Deflection Analysis

Performance Criteria	Unsatisfactory	Developing	Satisfactory	Exemplary
6a. Beam Setup and Configuration	Beam setup is improper and supports are misaligned, and loading is inconsistent.	Beam is partially set up correctly and minor alignment issues affect accuracy.	The beam is properly set up and alignment and loading are consistent and appropriate.	Beam setup is precise and all configurations are optimized, and alignment is thoroughly verified.
6b. Material Property Identification	Material properties are missing, or incorrectly identified and elastic modulus is not referenced.	Material properties are partially identified, and elastic modulus is estimated with errors.	Material properties are correctly identified, and elastic modulus is accurate and documented.	Material properties are determined with high accuracy and thorough documentation of property sources included.
6c. Deflection Measurement and Recording	Deflection data is incomplete, inconsistent, or incorrectly recorded and no clear trends observed.	Deflection data is partially recorded, and some trends are visible but with errors or omissions.	Deflection data is complete and accurately recorded and clear trends align with theoretical expectations.	Deflection data is comprehensive and precise, and trends are analyzed in depth with explanations for anomalies.
6c. Theoretical and Experimental Comparison	No effort to compare theoretical and experimental results and variations are unexplained.	Basic comparison is made, and variations are noted but not thoroughly analyzed.	Comparison is thorough and discrepancies are explained with consideration of experimental errors.	Comparison is insightful and detailed, and variations are analyzed deeply, with innovative solutions proposed.
6c. Application of Beam Deflection Formulas	Formulas are incorrectly applied or missing and theoretical values are not calculated.	Formulas are applied but with significant errors and theoretical values are partially calculated.	Formulas are correctly applied and theoretical values align with experimental trends.	Formulas are precisely applied and theoretical values are calculated with clarity and detailed derivations.
6c. Interpretation and Reporting	The report lacks clarity or completeness, and no meaningful interpretation of results is provided.	The report is partially complete, and results are interpreted but lack depth or connections to objectives.	The report is clear and complete, and the results are well interpreted and connected to learning objectives.	The report is highly detailed and insightful, and results are interpreted comprehensively with critical analysis.
6d. Engineering Judgment and Conclusions	No conclusions are drawn or they are disconnected from the experimental outcomes.	Some conclusions are presented but lack clarity or fail to relate trends to real-world implications.	Conclusions are reasonable and supported by analysis of results and sources of error.	Conclusions demonstrate strong engineering judgment, with thoughtful discussion of trends, experimental limitations, and practical applications.

2.1.4 Tensile Testing at Extreme Temperatures (In Process)

Objective:

To investigate the effects of extreme temperatures on material behavior, including changes in yield strength, ultimate tensile strength, % elongation, ductility and fracture characteristics.

Procedure:

- Students prepare specimens made of material such as aluminum, steel, or polymer, while following the corresponding ASTM standards for tensile testing. Students are encouraged to choose composite materials as well [17]. At WIT, students are likely to be provided with flat bar samples made of three different materials (preferably steel, brass and aluminum).
- The tensile testing machine is equipped with a heating/cooling chamber to achieve controlled temperature environments ($-20°C$, room temperature, and $200°C$).
- Specimens are soaked at the target temperature for a specified duration to achieve uniform thermal equilibrium during testing.
- Incremental tensile loads are applied until specimen failure, and stress-strain data is recorded throughout the test.
- Key properties such as elastic modulus, yield strength, ultimate tensile strength, elongation, and fracture characteristics are extracted from the stress-strain curves.
- Students analyze the temperature dependent trends in mechanical properties and compare these with published database[18].
- The results are summarized, and variations are discussed, with potential sources of error identified (thermal gradients, specimen handling and inherent material inconsistencies).

Learning Outcomes: At the end of this lab module, students should be able to:

- Evaluate the effect of temperature on material properties such as $E, \sigma_y,\ UTS\ and\ \varepsilon_f$.
- Conduct tensile testing on machines under controlled thermal environments.
- Interpret stress-strain curves and explain temperature dependent trends in mechanical behavior of different materials.
- Apply engineering judgment to assess experimental limitations and suggest improvements particularly related to thermal gradient.

Challenges:

- Making sure that the specimen temperature throughout the test is uniform, especially for thicker materials.
- Managing thermal gradients that may introduce inaccuracies in stress-strain data.
- Mitigating potential equipment limitations, such as consistent chamber heating/cooling rates or machine calibration at extreme temperatures.
- Safely handling materials and equipment during testing at extreme temperatures.
- Addressing variability in material properties or manufacturing imperfections in the specimens if these students are yet to take a course in materials science [12].

Instructors who wish to incorporate *Tensile Testing at Extreme Temperatures module* as part of their SO6 assessment for the Mechanics of Materials course can refer to the recommended assessment rubric provided in **Table 5**.

Table 5: Recommended Assessment Rubric for Tensile Testing at Extreme Temperatures

Performance Criteria	Unsatisfactory	Developing	Satisfactory	Exemplary
6a. Specimen Preparation	Specimens are improperly prepared or not dimensioned according to standards.	Specimens are prepared but with minor deviations from standard dimensions or material requirements.	Specimens are properly prepared, and dimensions and materials meet standards.	Specimen preparation is meticulous, and all dimensions and material properties are documented in detail.
6b. Temperature Control and Monitoring	Temperature is not controlled or monitored effectively, and test conditions are inconsistent.	Temperature control is partially consistent, and monitoring is incomplete or inaccurate.	Temperature is controlled and monitored accurately, and test conditions are stable.	Temperature control is precise, and thermal uniformity is achieved and recorded comprehensively.
6c. Stress-Strain Analysis	Stress-strain data is incomplete or incorrectly plotted and temperature effects are not evaluated.	Stress-strain curves are partially plotted and basic trends identified but with calculation errors.	Stress-strain curves are accurately plotted and temperature effects on material behavior are discussed.	Stress-strain analysis is thorough and insightful and detailed evaluation of temperature dependent material properties included.
6d. Engineering Judgment and Conclusions	No conclusions are drawn; student shows no understanding of experiment implications.	Basic conclusions are presented but lack justification or connection to engineering principles.	Reasonable conclusions are drawn based on data and supported with relevant engineering reasoning.	Conclusions are thoughtful, well-supported, and demonstrate strong engineering judgment regarding temperature effects and experimental limitations.

2.1.5 Buckling of Slender Columns (In Process)

Objective:

To investigate the buckling behavior of slender columns under axial compressive loads, compare experimental results with theoretical predictions based on Euler's buckling theory, and analyze the effect of column material, geometry, and boundary conditions.

Suggested Procedure:

- Prepare columns of different materials (steel, aluminum, and wood or brass) with varying lengths and cross-sectional geometries (circular, square, and rectangular if possible).
- Column boundary conditions are set up to replicate pinned-pinned, fixed-fixed, and fixed-free configurations using specialized end supports.
- Columns are incrementally loaded axially using a compression testing machine until buckling occurs.
- Critical buckling loads are recorded, and lateral deflections are recorded using dial gauges.
- Theoretical buckling loads are calculated using Euler's formula: $P_{cr} = \frac{\pi^2 EI}{(KL)^2}$; where:
    1. P_{cr}, Euler's critical load (longitudinal compression load on column)
    2. E Young's modulus of the column material
    3. I, second moment of area of the cross section of the column (area moment of inertia)
    4. L, unsupported length of column
    5. K, column effective length factor
- Experimental results are compared with theoretical values, and inconsistencies are analyzed.
- Students evaluate the effect of material properties, geometry, and boundary conditions on buckling behavior and discuss any deviations from theoretical assumptions.

Learning Outcomes: At the end of this lab module, students should be able to:

- Apply the principles of column buckling and derive Euler's buckling formula.
- Set up and conduct buckling experiments under different boundary conditions.
- Calculate critical buckling loads and interpret discrepancies between theoretical and experimental results. Numerical simulations can be performed with instructor's guidance.
- Assess the practical implications of column stability in engineering structural applications.

Challenges:

- Proper alignment of the column to avoid unintended eccentricity in loading.
- Accurately replicating theoretical boundary conditions during the experiment.
- Managing variability in material properties and imperfections in column manufacturing.
- Measuring small lateral deflections near the onset of buckling without disrupting the test setup.

Instructors who wish to incorporate *Buckling of Slender Columns module* as part of their SO6 assessment for the Mechanics of Materials course can refer to the recommended assessment rubric provided in **Table 6**.

Table 6: Recommended Assessment Rubric for Buckling of Slender Columns

Performance Criteria	Unsatisfactory	Developing	Satisfactory	Exemplary
6a. Specimen Alignment and Preparation	The specimen is improperly aligned and critical dimensions are missing or incorrect.	Specimen is partially aligned and some dimensions deviate from theoretical requirements.	Specimen is aligned and prepared accurately and critical dimensions meet requirements.	Specimen alignment is flawless and dimensions are carefully measured and verified.
6b. Load Application and Observation	Load is applied unevenly or outside acceptable limits and buckling behavior not observed.	Load application is inconsistent and buckling behavior partially observed but with unclear trends.	Load is applied evenly and buckling behavior is accurately observed and documented.	Load is applied with high precision and buckling observations are detailed and reproducible.
6c. Critical Load Determination	Critical load calculation is missing or incorrect and no effort to correlate with Euler's formula.	Critical load is calculated but with errors and limited correlation with theoretical predictions.	Critical load is calculated accurately and theoretical and experimental results align well.	Critical load is determined with precision and detailed analysis of variations and imperfection effects included.
6d. Engineering Judgment and Conclusions	No conclusions are drawn; student shows no understanding of experimental implications.	Basic conclusions are presented but lack justification or connection to engineering principles.	Conclusions are supported by data and reflect reasonable engineering analysis.	Conclusions demonstrate deep insight and sound engineering judgment, with thoughtful discussion of boundary condition effects and test limitations.

2.1.6 Thermal Stress in Bimetallic Strips Lab Module (In Process)

Objective:

To study the thermal stress and deformation in bimetallic strips subjected to temperature changes, and analyze the relationship between material properties, temperature variation, and bending behavior [19].

Suggested Procedure:

- Students prepare bimetallic strip specimens made of two materials with different coefficients of thermal expansion (steel and brass or aluminum and steel).
- Strips are clamped at one end to simulate a cantilever configuration, leaving the other end free to bend under the effect of temperature.
- Specimens are gradually heated or cooled using a controlled temperature source and safety is monitored carefully and constantly.
- The amount of curvature or deflection at the free end is measured using displacement sensors or dial gauges for various temperature increments. Thermocouples can also be implemented to record the deflection vs temperature trend in different strips.
- Students calculate theoretical thermal stress and bending deflection[19].
- Experimental data is compared with theoretical calculations, and variations are analyzed, considering factors such as thermal gradients, material imperfections, and boundary conditions.
- Students discuss practical applications of bimetallic strips, such as in thermostats or temperature sensors, and their implications for engineering structural design.

Learning Outcomes: At the end of this lab module, students should be able to:

- Apply the concept of thermal stress and its relationship to material properties and temperature changes.
- Measure thermal deformation and analyze the bending behavior of bimetallic strips.
- Interpret experimental data and assess the practical implications of thermal stress in engineering systems.

Challenges:

- Achieving uniform heating or cooling of the bimetallic strip to avoid thermal gradients.
- Minimizing measurement errors when recording small deflections of bimetallic strip.
- Students' ability to comment on variability in material properties and inconsistencies in strip bonding [20].
- Managing the effects of environmental factors such as air currents or uneven heat distribution on experimental results without prior knowledge of heat transfer.

Instructors who wish to incorporate *Thermal Stress in Bimetallic Strips module* as part of their SO6 assessment for the Mechanics of Materials course can refer to the recommended assessment rubric provided in **Table 7**.

Table 7: Recommended Assessment Rubric for Thermal Stress in Bimetallic Strips

Performance Criteria	Unsatisfactory	Developing	Satisfactory	Exemplary
6a. Specimen Assembly and Preparation	Bimetallic strip is improperly assembled, and material selection is incorrect or unclear.	The specimen is partially assembled and thermal properties of materials not well matched or poorly documented.	Specimen is correctly assembled and materials chosen are appropriate and documented.	Specimen preparation is precise, and materials are chosen to demonstrate distinct thermal expansion properties.
6b. Heating and Temperature Monitoring	Heating method is ineffective or inconsistent and temperature measurements are inaccurate or missing.	Basic heating setup completed, and temperature variations are monitored but with significant errors.	Heating is consistent and temperature is accurately recorded at all points on the bimetallic strip.	Heating setup is optimized and temperature uniformity is achieved and recorded in detail.
6c. Measurement of Curvature and Stress	Curvature data is missing, inconsistent, or incorrectly interpreted and has no connection to thermal stress.	Curvature is partially measured and thermal stress values calculated but with errors.	Curvature is measured accurately, and thermal stress is calculated and matches theoretical values.	Curvature and thermal stress are measured with high precision and detailed discussion of results and variations with theory.
6d. Engineering Judgment and Conclusions	No conclusions are drawn or analysis is disconnected from engineering context.	Some discussion of results, but lacks depth or clarity in identifying sources of error or design implications.	Results are interpreted with reasonable analysis, identifying key sources of variation and connecting to theory.	Conclusions show strong engineering judgment with thoughtful interpretation of trends, limitations, and implications for real-world applications.

2.3 Integration of Theory, Experimentation, and Simulation

To comprehensively assess SO6, these new labs in the Mechanics of Materials curriculum should aim to include at least two of any three of the foundational components: 1) Theoretical Analysis, 2) Experimental Testing, 3) Numerical Simulation

2.2.1 Theoretical Analysis

This component enables students to develop a fundamental understanding of the underlying mechanics of materials concepts by deriving analytical models that predict experimental outcomes. Based on the curriculum developed for WIT, these six labs integrate fundamental concepts from solid mechanics, including stress-strain relationships, material constitutive laws, beam deflection, and buckling analysis. Using appropriate simplifications, assumptions and boundary conditions, students can derive equations or use preexisting models or formulas to calculate expected results. For instance, for stress concentration around a circular hole, students can use classical stress equations given in the mechanics of materials textbooks to estimate stress amplification [7], [10]. Buckling, thermal stress in bimetallic strips, failure characteristics of riveted connections are also elaborately explained in the textbooks and having a deeper understanding of these concepts will only further reinforce the other two components: experimentation and simulation.

2.2.2 Experimental Testing

The fact that SO6 aims to assess students' ability to develop and conduct experiments, these lab modules can provide unprecedented knowledge and experience in conducting mechanical tests, gathering data, and analyzing real world material behavior particularly under controlled conditions. Students' ability to set up and execute experiments using standard laboratory equipment, such as tensile testers, strain gauges, DIC, and displacement sensors, will help them prepare for situations with ambiguity or limited information. Further emphasis on calibration techniques to achieve measurement accuracy and experiment repeatability can also be beneficial to create ideal lab manuals for other students to follow. The variations in the experimental and theoretical results can help students learn more about real-world complexities like material heterogeneity, imperfections, and measurement errors and source of errors.

2.2.3 Numerical Simulation

Theoretical and experimental results augmented by the numerical simulation will further help students learn about the limitations of experimentations and prototyping. Although not expected, students have an opportunity to go above and beyond and learn about Finite Element Analysis (FEA) tools such as ANSYS, ABAQUS, or SOLIDWORKS Simulation on their own to model the same systems studied experimentally by applying the appropriate boundary conditions. Instructors can also provide relevant materials such as tutorials and notes in the form of steps or directions needed to successfully complete the simulation. We believe that FEA simulation software enables students to explore complex geometries, boundary conditions, and loading scenarios that may be impractical or time consuming to replicate in the lab. Students learn to refine mesh quality, apply appropriate material properties, boundary conditions, and interpret simulation outputs like stress contours, deformation plots, and safety factors. By doing so, students can interpret numerical data and integrate it with theoretical and experimental results.

The combination of theoretical analysis, experimental testing, and numerical simulation ensures that students develop a holistic understanding of open-ended engineering problems. This methodology not only reinforces learning through multiple modalities but also reflects the iterative process used in professional engineering practice to design, analyze, iterate, replicate and validate solutions.

3. Results and Discussion

Of all six proposed labs, only one lab module, Testing of Riveted Connections has been implemented and assessed so far at the end of Fall 2024 semester (Started in September). The results are shown in **Figure 1**.

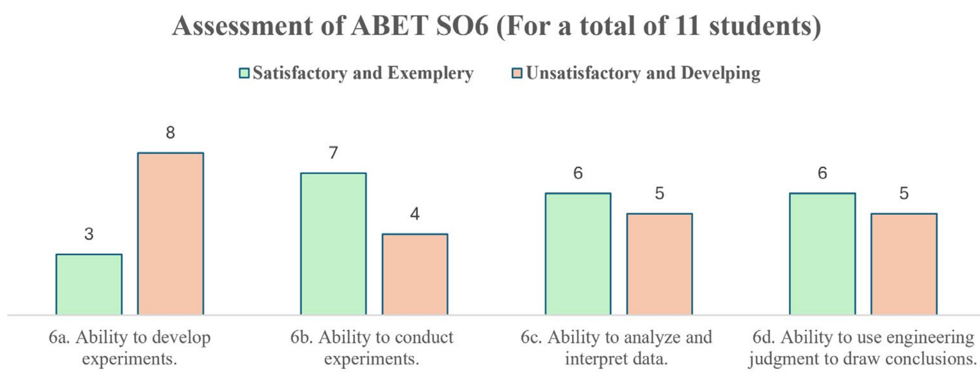

Figure 1: SO6 Assessment Data for Testing of Riveted Connections conducted in Fall 2024 semester

While the results are not particularly encouraging it is a step forward to understanding where students fell short and what else could have been done to ensure a better outcome. One of the main pillars of SO6 is for students to be able to develop an experiment. As can be seen from the **Figure 1** that 6a, Ability to develop experiment fell disappointingly short of expectations (only 27% of the students were able to develop this experiment). On the other hand, having done several experiments prior to this experiment, the majority (63%) of the students were able to conduct the experiments with basic understanding of Instron and incremental load. SO 6c, Ability to analyze and interpret data and SO 6d, Ability to use engineering judgment to draw conclusions can often be looked at from two different lenses. Theoretical formulation vs experimental prowess itself. Courses like Mechanics of Materials often have a diverse mix of student skill levels. As a result, approximately 50% of students demonstrate satisfactory or developing proficiency in SO 6c and SO 6d. This experiment was conducted toward the end of the semester, a time when students are typically focused on preparing for final exams. This may have contributed to a lack of motivation to engage fully with the experiment. It should also be noted that, none of the students attempted the open-ended design problem, which is a major concern that we plan to address in the upcoming Spring 2025 semester.

4. Future Direction and Recommendations

Based on the assessment data for Testing of Riveted Connections collected from Fall 2024 semester, we gained a deeper insight into students' learning challenges and areas of continuous improvement. It is concerning that only 27% of students successfully developed an experiment, indicating a significant need for stronger support in guiding students toward independent lab design. While 63% of students were able to conduct and collect the data, nearly 50% of the students struggled with data interpretation and applying engineering judgment to draw conclusions, suggesting a gap in their ability to correlate theoretical concepts with experimental outcomes. These findings prompt us to revisit the curriculum of Mechanics of Materials (particularly previous labs) to introduce more structured pre-lab activities that can help students gradually transition from instructor-led exercises to more open-ended experimental design. Furthermore, to address any specific student challenges, we plan to include some formal training or workshops on topics like strain gauge application, DIC, FEA Simulation tutorials and faculty and staff led troubleshooting sessions. We plan to use this (and any other SO6) assessment data for an iterative lab development process, to further refine lab instruction, learning outcomes, improve assessment rubrics, and adjust the complexity of experiments to ensure smooth progression of students' skills. We plan to share these results with other faculty members teaching the same course in the future to ensure an alignment between theory and experimentation and to create a more cohesive and effective approach to assessing SO6 within the program.

With this paper, we aim to inform instructors about the wide range of experiments that can be utilized to assess SO6 within the Mechanics of Materials course in a mechanical engineering curriculum. In Spring 2025, we plan to begin assessment with the Beam Deflection module. This module was selected primarily due to the immediate availability of equipment, for smooth and tangible implementation. We intend to introduce this module to students in March 2025 (since the semester concludes in April 2025) and evaluate its impact, particularly on students' ability and willingness to tackle open ended design problems. Other labs, such as Stress Concentration Analysis Around a Circular Hole and Tensile Testing at Extreme Temperatures, are underway but currently face challenges due to funding constraints. It is recommended that instructors apply and secure internal grant opportunities within their institutions to develop and implement these newer modules. Thermal Stress in Bimetallic Strips will likely be our next focus, as it requires only basic equipment and manufacturing skills, with plenty of resources available to support its development. Buckling of Slender Columns, however, poses more significant challenges for two reasons: (1) limited time in a 15 weeklong semester prevents a deeper understanding of its theoretical aspects, and (2) the current lack of resources to secure or build buckling test equipment. Nonetheless, we will continue to pursue internal grants of various scales to support the development or refinement of these labs. Additionally, we aim to engage students, particularly those unable to secure Co-op placements, by involving them in lab-related projects. These could include sample preparation, troubleshooting manufacturing machines, and contributing to peer learning initiatives, further enriching their educational experience.

5. Conclusion

The development and incorporation of innovative labs in the Mechanics of Materials course aligns with ABET SO6 requirements, fostering critical thinking, problem solving, and experimental skills with minimum supervision. By integrating theoretical analysis, hands-on experimentation, and numerical simulations, these proposed six labs prepare students for real world engineering challenges. The detailed lab modules, assessment rubric, and instructional resources presented in this paper provide a comprehensive framework for implementing these practices in undergraduate mechanical engineering curricula. We welcome collaboration with fellow faculty members working in this area to refine these modules or to develop entirely new ones.

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