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Integrating Design Projects to Help Students Learning in Mechanical Engineering Lab

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Integrating Design Projects to Enhance Student Learning in Mechanical Engineering Laboratories

Abstract

The Mechanics Laboratory course serves as a critical bridge between theoretical knowledge and practical engineering applications in the mechanical engineering curriculum. This three-credit course incorporates hands-on learning in areas such as material mechanics, vibration analysis, and computer-aided data acquisition while developing key engineering competencies, including measurement techniques, data interpretation, error analysis, and technical communication. Students are assessed through lab reports, homework, quizzes, collaborative design projects, and active engagement, with detailed laboratory documentation required.

A cornerstone of the course is the design project, where students independently conceptualize, execute, and analyze an engineering experiment. These projects encompass problem definition, instrumentation selection, data processing, and comprehensive reporting, providing students with real-world engineering problem-solving experience.

This paper presents an overview of student-led design projects, outlines challenges faced, and explores innovative solutions implemented to enhance learning outcomes. The study underscores the effectiveness of integrating experiential learning into engineering curricula to better prepare students for professional careers.

Introduction

Laboratory courses are integral to engineering education, allowing students to apply theoretical principles through hands-on experiences. The Mechanics Laboratory course, a required component of the mechanical engineering curriculum, provides students with valuable skills in material mechanics, vibration analysis, and data acquisition. In addition to technical knowledge, the course emphasizes critical skills such as data analysis, error evaluation, and technical communication, essential for engineering practice. The course accommodates approximately 30 students, divided into two sections of 15 students each.

ABET Criterion 3 states that "engineering programs must demonstrate that their graduates have an ability to design a system, component, or process to meet desired needs." However, design instruction is typically limited to freshman and senior years, with little emphasis during the sophomore and junior years as students focus on engineering science courses [1-3].

This fragmented approach limits opportunities for students to develop design skills, hindering knowledge retention and leaving them underprepared for design-focused careers [4-5]. Bruner [6] suggests, learning is a constructivist process, requiring multiple, meaningful interactions with content. To build strong design competencies, students need consistent engagement with the engineering design process throughout their education.

A distinctive aspect of the course is the design project, which mirrors real-world engineering processes, from problem formulation to experimentation and data interpretation. This project-based approach strengthens theoretical understanding while fostering practical skills such as teamwork, documentation, and adherence to engineering constraints.

This paper discusses the Mechanics Laboratory course structure, highlights student-led design projects, and examines the associated challenges and solutions. The study aims to showcase how this approach prepares students for engineering careers through experiential learning.

Course Format

The course is structured as follows:

- Weeks 1-2: Lectures covering fundamental topics, including error analysis, data acquisition, and uncertainty analysis.
- Weeks 3-7: Students perform five structured experiments covering tension, torsion, vibration, stress concentration, and thin-walled pressure vessels.
- Weeks 8-14: Students work in teams to design and execute an independent experiment.

The course aligns with ABET accreditation criteria and supports student outcomes, including:

- The ability to identify and solve complex engineering problems.
- The ability to apply engineering design to meet real-world constraints.
- Effective communication with diverse audiences.
- The ability to conduct experiments, analyze data, and apply engineering judgment.
- The ability to work collaboratively in teams.
- The ability to acquire and apply new knowledge through appropriate learning strategies.

Design Projects

The final design project allows students to synthesize their learning by designing and conducting an open-ended experiment. Teams of three to four students collaborate on projects requiring significant in-class and independent work. Each team submits a comprehensive report, with all members expected to contribute equitably and develop a thorough understanding of the entire project.

Example Student Projects

1. Comparison of Cast and Forged Car Pistons – Analyzed the mechanical properties of aluminum pistons using SolidWorks and ANSYS simulations to assess deformation, stress, and strain characteristics.
2. Evaluation of Smartphone Case Strength – Conducted drop tests to evaluate material durability and impact resistance in protective smartphone cases.

3. Structural Analysis of a Skateboard Truck – Used strain gauge testing and ANSYS simulations to assess impact performance and material selection.
4. Identifying the Sweet Spot of an Aluminum Baseball Bat – Applied beam strain testing to determine optimal impact locations for maximizing performance.
5. Force Analysis for Crushing Cans – Designed an optimized can crusher incorporating a pre-buckling mechanism to reduce force requirements.

Sample Students Work

The semester-long design project provides an opportunity for students to define and execute an engineering challenge focused on measurement and data collection. This project simulates real-world engineering workflows and reinforces theoretical concepts covered in class. The hands-on experience guides students through the entire experimental process, from problem definition to final reporting.

Design Project 1: Comparison of Cast and Forged Car Pistons

This project analyzed the performance characteristics of two car pistons made from different materials: a cast aluminum 2024-T4 piston and a forged aluminum 4032-T6 piston. The study focused on total deformation, equivalent stress, equivalent strain, and thermal strain. Due to time constraints, physical testing was replaced with simulations. Both pistons were modeled in SolidWorks and analyzed using ANSYS software.

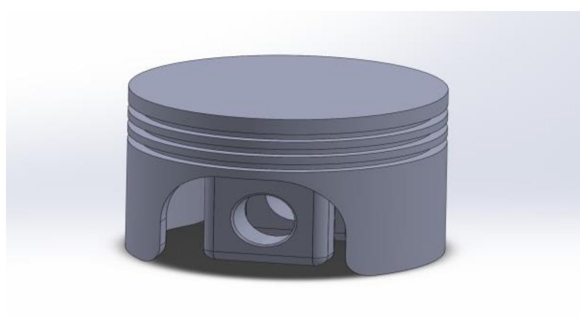

Figure 1 – Schematic of the Equipment Used in Lab

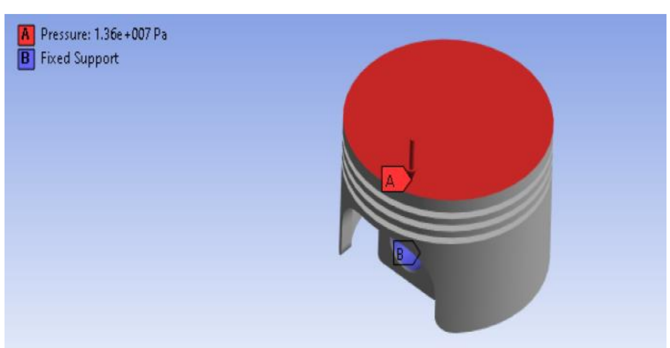

Figure 2 – Detail of the Equipment Load and Setup

Simulations applied pressure and uniform temperature conditions to each piston. Results indicated that the forged piston outperformed the cast piston, exhibiting lower deformation, stress, and thermal strain. The cast piston showed higher errors in total deformation, attributed to discrepancies between the simulated models and actual piston designs.

Type	Total Deformation (mm)	Thermal Strain (m/m)	Equivalent Strain (m/m)	Equivalent Stress (GPa)
Cast 2024 Aluminum	0 - 3.52	0 - 0.037	0.00001 - 0.14	0.00064 - 10.46
Forged 4032 Aluminum	0 - 2.89	0 - 0.031	0.00001 - 0.12	0.00066 - 96.89

Table 1: Performance Data

The models were based on the dimensions of market products, specifically the Toyota 2AZ-FE cast piston and the Chevrolet small block 5.7L/350 forged piston. The simulation replicated engine conditions, including typical pressure and thermal loads of 13.6 MPa and 1500°C, respectively.

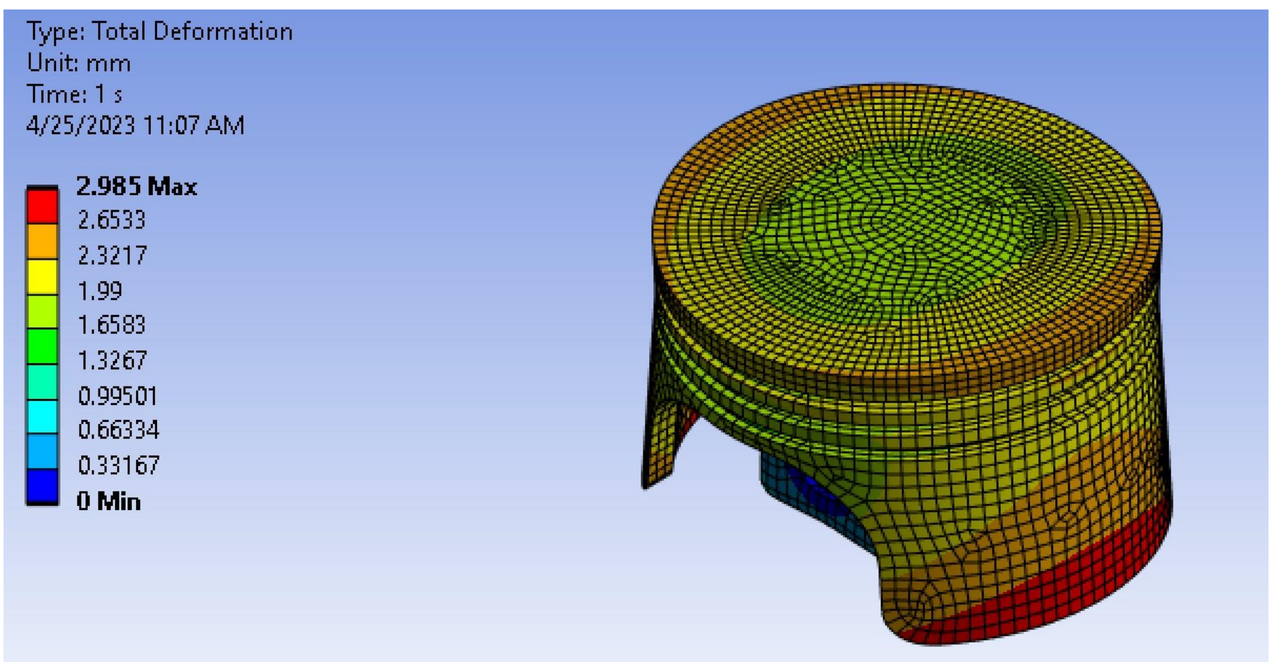

Figure 3: Cast Piston Total Deformation Solution

As shown in Figures 3 and 4, the forged piston demonstrated superior resistance to pressure and

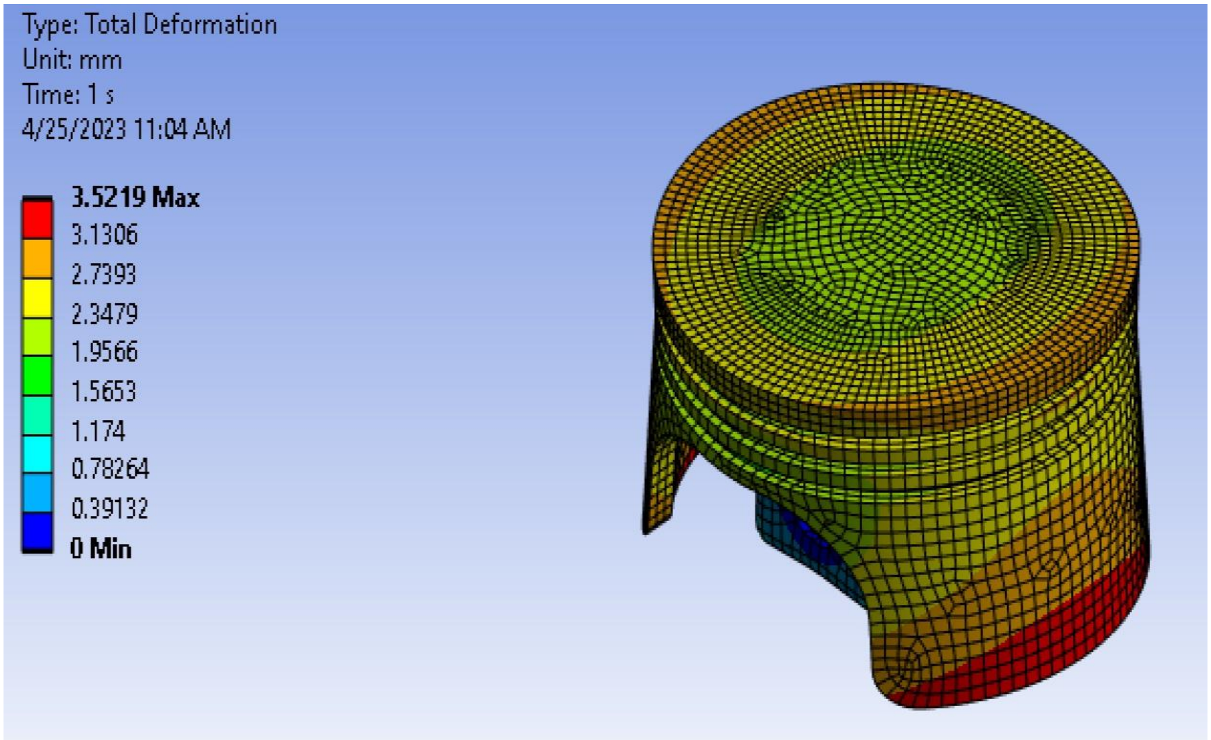

Figure 4: Forged Piston Total Deformation Solution

temperature compared to the cast piston. This performance advantage stemmed from its material composition—aluminum 4032-T6—whose properties and grain orientation significantly enhanced its strength. As a result, the forged piston exhibited greater resistance to deformation, stress, and strain than the cast piston.

Design Project 2: Evaluation of Smartphone Case Strength and Protection

This project evaluated the durability of five smartphone cases—two soft, two hard, and one hybrid—using an iPhone 7. Drop tests were conducted from heights of 3, 4, 5, and 6 feet. The hybrid shock-absorbing case provided the best protection, while the other cases sustained significant damage at higher drop heights. The study highlighted trade-offs between shock absorption and material durability, offering valuable insights for selecting effective protective cases .Figures 5 and 6, show ANSYS analysis of the deformation of the drop test..

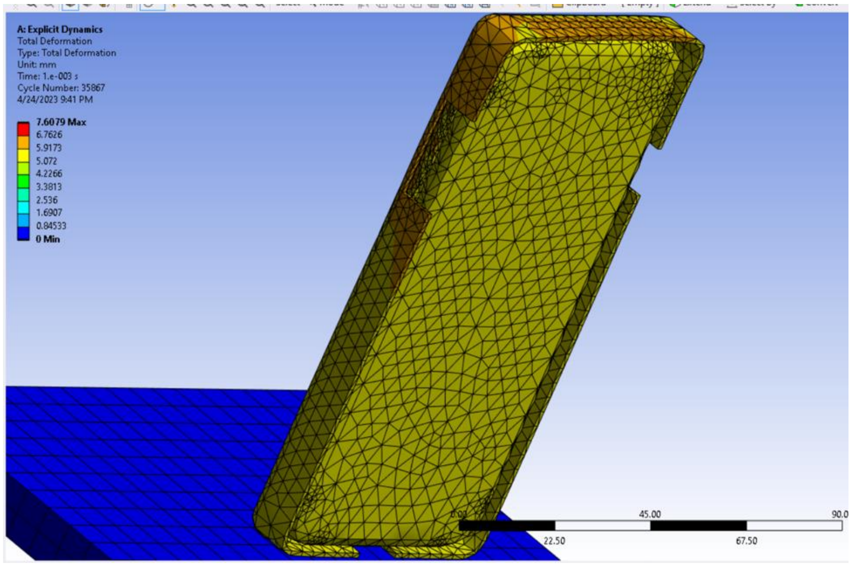

Figure 5: this model shows the test results from the deformation of the drop test from ANSYS.

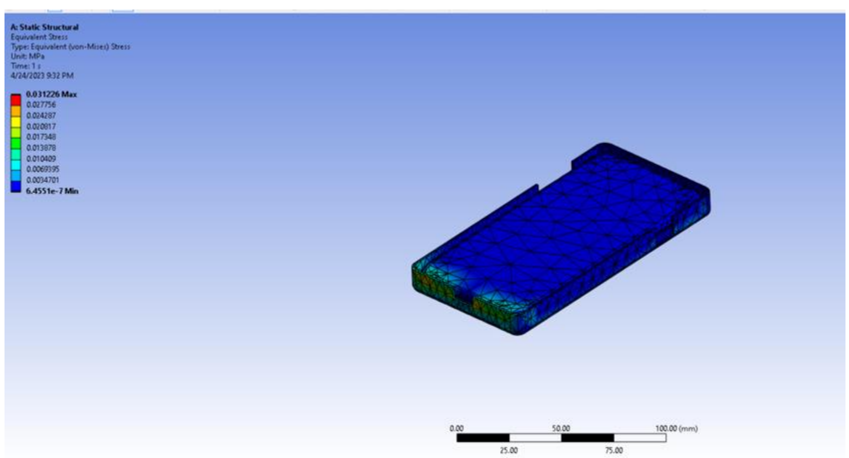

Figure 6: Flat force deformation. Shows the location of where the force was applied.

Results

The calculated fall impulse data for tile and concrete surfaces are presented in Table 2 and Table 3, respectively. Acceleration data recorded during the experiment and impulse force were calculated.

Without Case			
Impulse (N·sec)	**Height (in)**	**Impulse (N·sec)**	**Height (in)**
0.024	34	0.016	34
0.049	48	0.029	48
0.137	64	0.089	64

Table 1: Tile floor test impulse comparison

Without Case		With Case	
Impulse (N·sec)	**Height (in)**	**Impulse (N·sec)**	**Height (in)**
0.009	34	0.008	34
0.023	48	0.014	48
0.025	64	0.019	64

Table 2: Concrete floor test impulse comparison

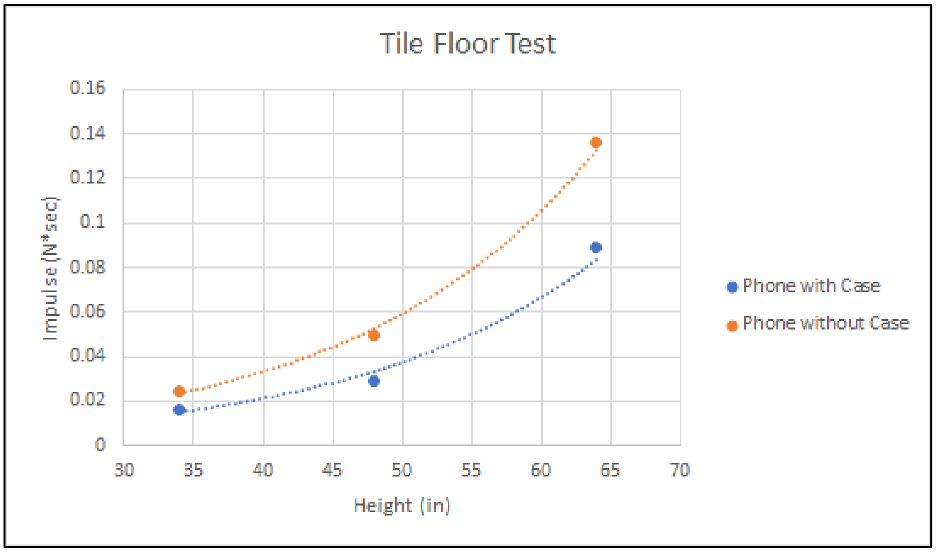

Figure 7: Comparison of impulse for the phone with and without the case over the tile floor. The phone did not receive any noticeable screen damage after both drop modes.

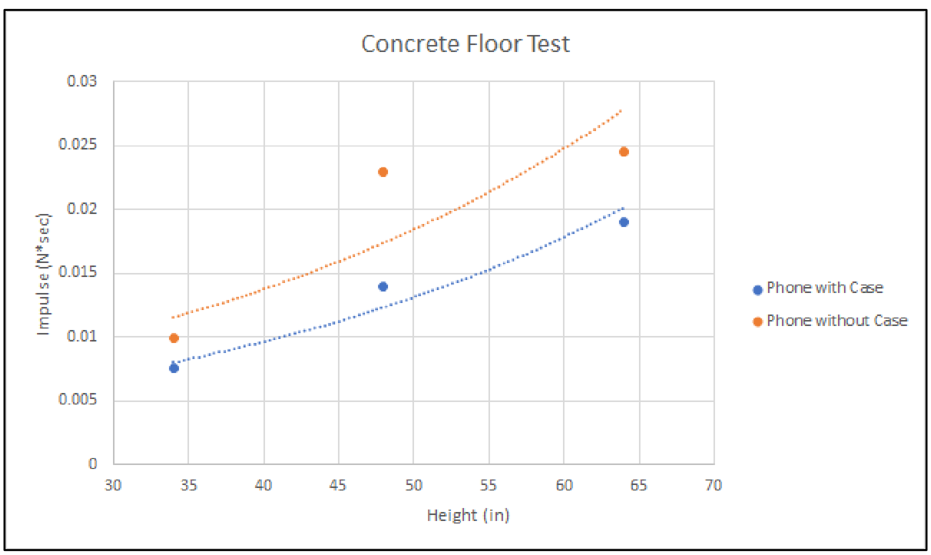

Figure 8: Comparison of impulse for the phone with and without the case over the concrete floor. After the final drop without the case, the phone screen's lower right corner shattered leaving the screen unusable on that portion.

Key Results:

- **Impulse Reduction:** Cases reduced impulse by up to 43% on tile floors and 32% on concrete surfaces.
- **Damage Patterns:** Phones without cases exhibited shattered screens at higher drops, whereas phones with cases experienced only minor damage.

Design Project 3: Structural Analysis of a Skateboard Truck under Impact

This study analyzed the deformation and stress experienced by a skateboard truck subjected to a simulated 14-foot-9-inch drop. Both ANSYS simulations and physical strain gauge tests were employed. The project evaluated six alternative materials for the truck, identifying Aluminum Alloy T6 as the most cost-effective option due to its balance of strength and cost.

Theory

Understanding the physics behind skateboarding is essential before analyzing the results. When a skateboarder drops from a 15-foot height, the board experiences both the force of the falling rider and the impact force on the ground. The impact velocity is given by:

$$v = \sqrt{2gh} \qquad (1)$$

where g is the acceleration due to gravity and h is the drop height. This velocity is used to calculate the momentum force on the skateboard, as shown in Equation 2.

$$F = mv \qquad (2)$$

where m is the rider's mass and v is the impact velocity from Equation 1.
Strain gauges were essential for measuring deformation in the skateboard trucks, indicating their strength. They provided strain data, calculated using Equation 3.

$$\varepsilon = \frac{\Delta l}{l_0} \qquad (3)$$

where ε = strain, Δl = change in the length due to the force, and l_0 = the original length of the object before the force is applied. Strain data is useful when analyzing the strength of the material to determine multiple material properties and to determine if the material is going to be suitable for its specific use.

Sketch Drawing and photo of equipment

Figures 9–11 illustrate the physical setup and experimental test techniques used in the aluminum truck experiment. A strain gauge was attached to the truck and connected to a LabView system, enabling real-time data acquisition and analysis. This setup allowed for a direct comparison between the measured strain data and the simulated results.

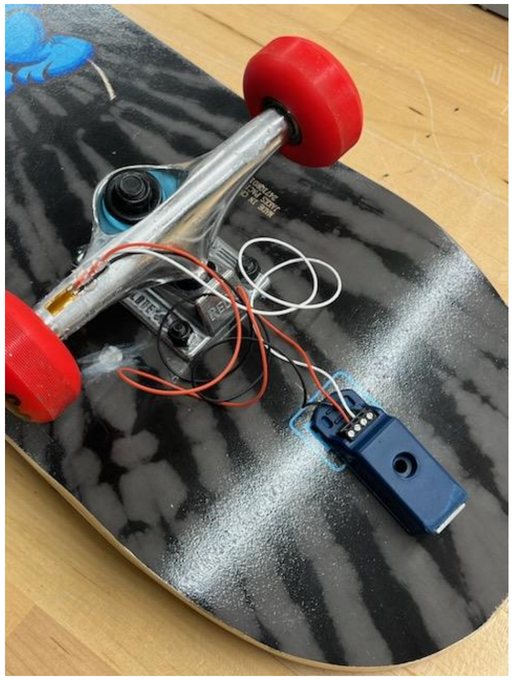

Figure 9– Strain Gage application for LabView Results of Aluminum Truck Deformation

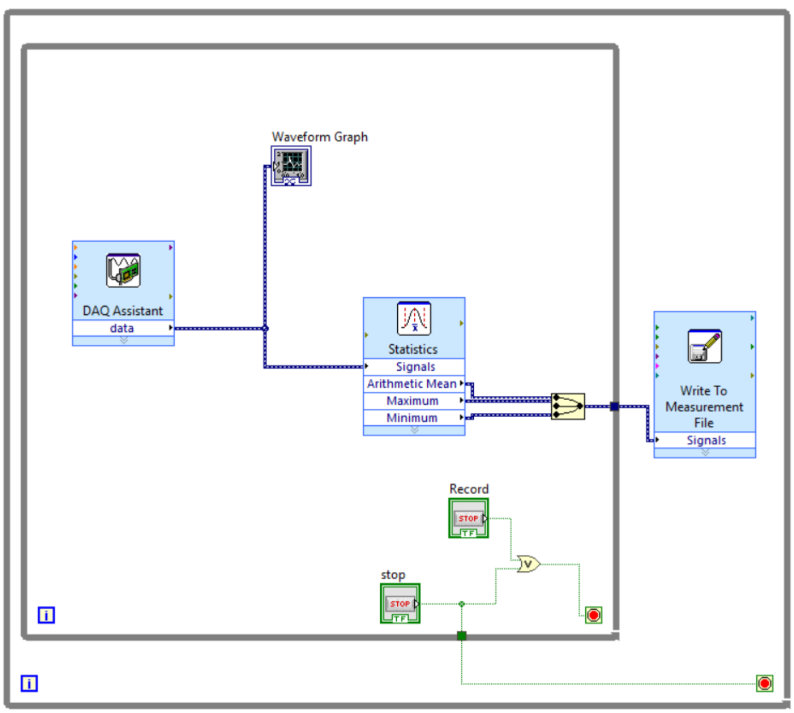

Figure 10 – LabView Circuit diagram

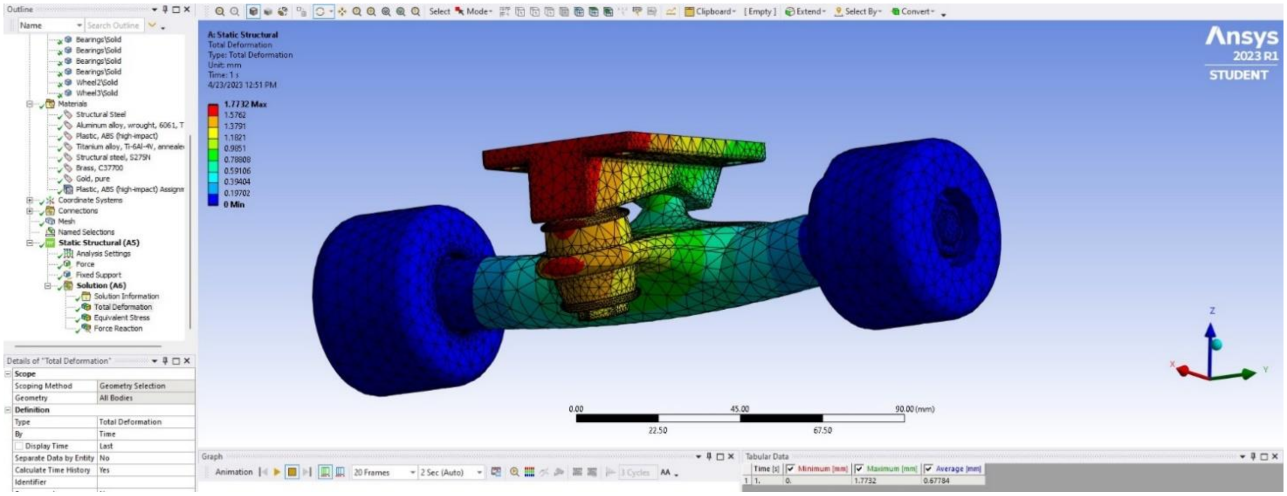

Figure 11: View of Plastic Truck Failure

Results Summary:

Material	Total Deformation (mm)	Equivalent Stress (MPa)
Aluminum Alloy T6	0.0898	26.79
Structural Steel	0.0478	32.39
Titanium Alloy	0.0675	30.24

Table 4 The Aluminum Alloy T6 truck's experimental and simulated deformations showed a 34.11% error, attributed to real-world inconsistencies.

A correlation was observed between the total deformation and the stresses experienced in the truck. As deformation decreased, slightly higher stress values were recorded, which aligns with the expectation that the bushing would endure greater stress when the truck absorbs less impact energy. The highest stress concentration was observed in the internal portion of the bushing.

Design Project 4: Identifying the Sweet Spot of an Aluminum Baseball Bat

This project identified the "sweet spot" of an aluminum bat using beam strain testing. Strain gauges mounted along the bat measured strain as a baseball was dropped from a consistent height. The results determined the sweet spot to be between 13 and 17 cm from the top of the bat, with a 3.4% error margin.

The findings suggest that beam strain testing is an effective method for locating the sweet spot in aluminum bats and potentially wooden bats. Additionally, this technique provides insight into the strain experienced by the bat when the ball makes contact at different locations.

Figure 12 – Complete Experimental Setup

Figure 12 illustrates the complete experimental setup used to identify the sweet spot of the baseball bat. The ball was suspended from a clamped wooden block, ensuring consistent impact height with each strike. The bat was securely clamped in a table vise, allowing for horizontal adjustments by repositioning the table. This setup enabled changes to the ball's contact location while keeping the rest of the experiment unchanged.

A strain gauge was mounted along the length of the bat to capture accurate readings upon impact. The gauge was wired to an NI 9944 device, which transmitted data to a computer for collection and analysis in LabView.

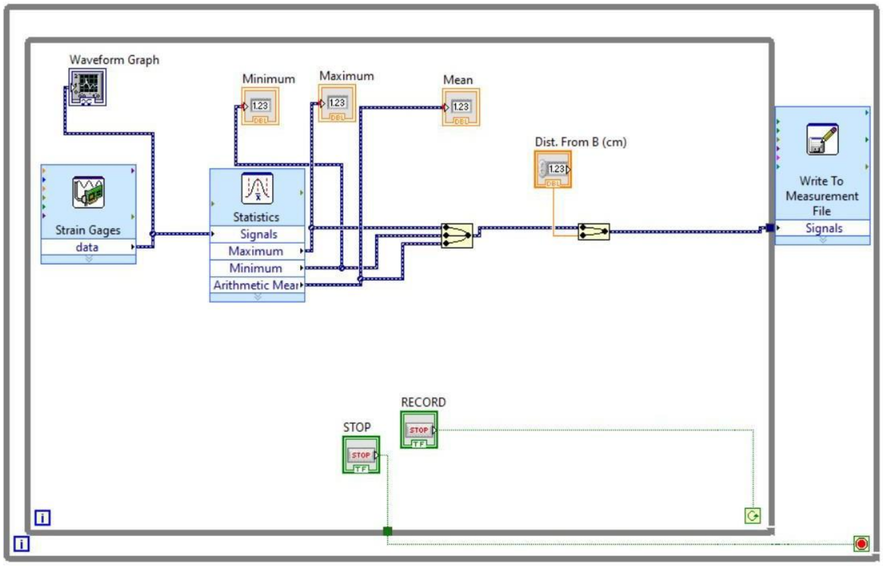

Figure 13– LabView Data Collection Software

Figure 13 illustrates the LabView VI designed to collect strain data from the strain gauges mounted on the baseball bat. The recorded strain measurements included minimum, maximum, and mean values, with the maximum strain used for data analysis in this study.

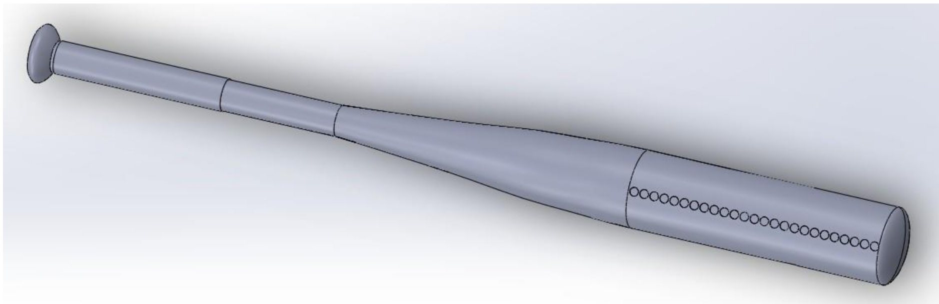

Figure 14 – Baseball Bat Created in SolidWorks

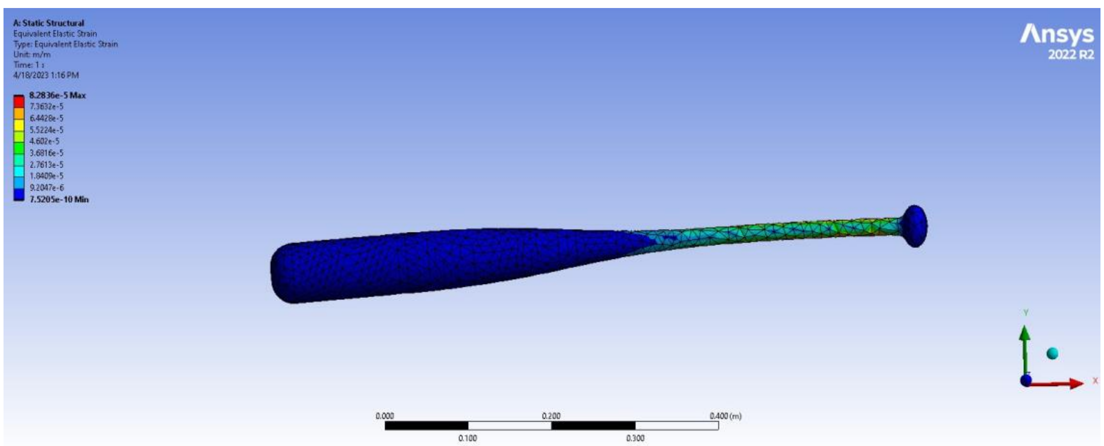

Figure 15 SolidWorks model

Figure 15 depicts the SolidWorks model of the baseball bat, which was used in Ansys to establish preliminary expectations for the experiment. All measurements were accurately transferred to the model, including a designated grip location and a series of evenly spaced contact points for analysis in Ansys.

Procedure:

- A baseball was dropped onto the bat at various points.
- Strain gauges collected data, which was analyzed in LabVIEW.

Insights: The method demonstrated potential for testing other bat types, offering a robust approach for evaluating strain distribution and impact response

Design Project 5: Optimizing Force Requirements for Crushing Cans

This project enhanced the design of a can crusher by integrating a pre-buckling mechanism to reduce the required crushing force. Tests conducted on various aluminum cans using a modified Eurolux Citrus Juicer, as shown in **Figure 16**, demonstrated that pre-denting lowered the force needed for buckling by more than 50%.

Figure 16– Eurolux Citrus Juicer

The experimental results were recorded using a juicer that was modified to allow it to crush cans and have a precision calibrated 5K load cell attached that displayed the maximum load applied to the can. The theoretical values for the loads were calculated using equations (4), (5),. These equations were retrieved from "Donnell Thin Wall Cylinder Buckling, published by NASA"..

$$\phi = 1/16 \sqrt{r\, t} \text{ (for } r\, t < 1500) \quad (4)$$

$$\gamma = 1 - 0.901(1 - e - \phi) \quad (5)$$

$$\sigma_x = \gamma E \,(3(1 - \nu 2)\, t/r)^{1/2} \quad (6)$$

$$F = \sigma_x A \quad (7)$$

Where: r = Radius, (in), t = Wall thickness, (in), A = Cross sectional area, (in^2), E = Young's modulus of elasticity (psi), γ = Knockdown Factor, ϕ = Correction Factor, σ_x = Buckling stress, (psi),v = Poisson's ratio F = Force (Lb).

Figure 17 presents the nonlinear results from the SolidWorks Simulation FEA, utilizing arc length control with the Newton-Raphson iterative technique. The standard 12 oz can showed a 29% error compared to the experimental values, the 12 oz slim can exhibited a 109% error, the 12 oz Coors can had a 42% error, and the 16 oz can displayed a 75% error.

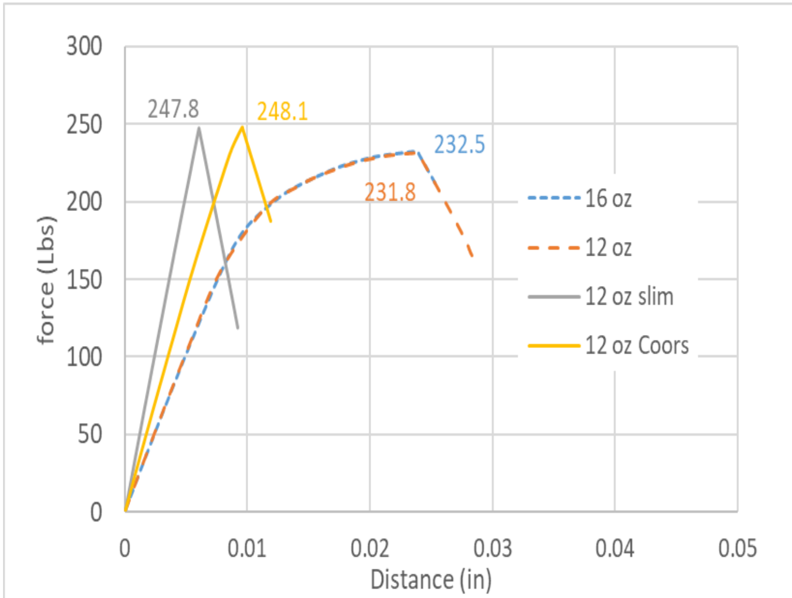

Figure 17: Force to Buckle from SolidWorks Simulation FEA nonlinear analysis.

The FEA results, however, revealed that the crushing process is initiated by buckling rather than reaching the material's yield strength. This is evident, as none of the four tests reached the 37,700 psi yield strength of the 3104-H19 aluminum used to manufacture the cans, as shown in Figures 19 and 20.

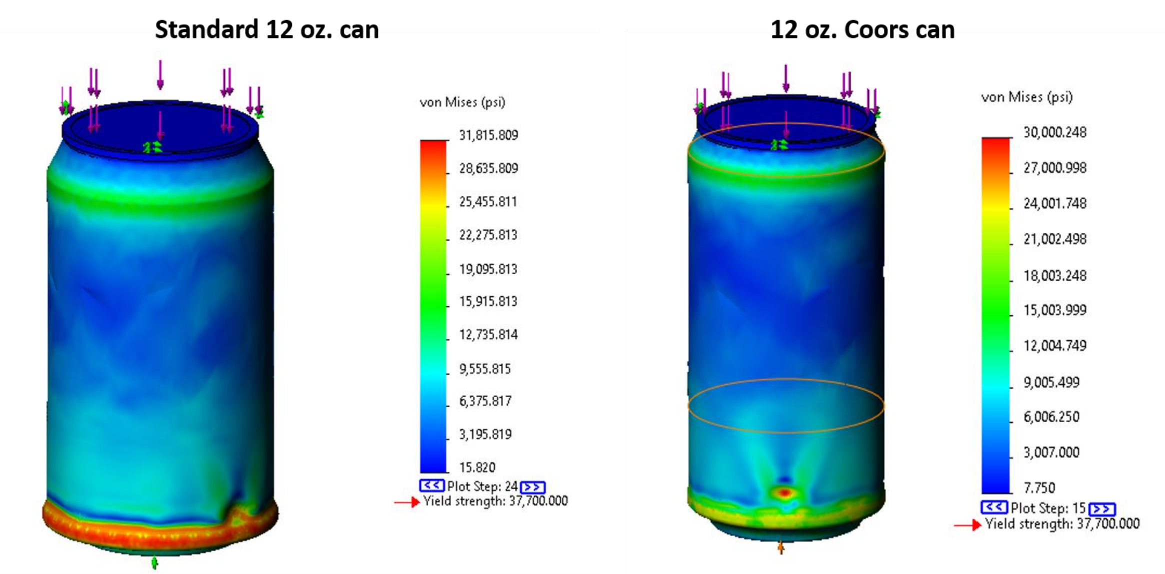

Figure 18: Standard 12 oz. can (left) and 12 oz Coors can (right) von Mises stress at buckling load performed through SolidWorks Simulation FEA nonlinear analysis.

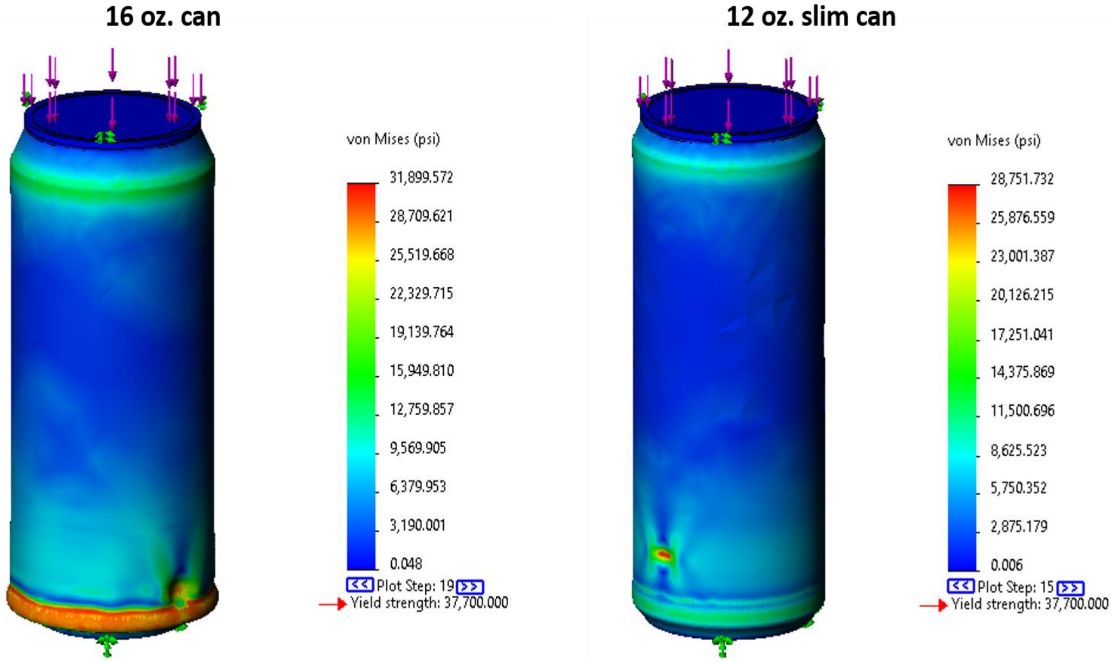

Figure 19: 16 oz. can (left) and 12 oz slim can (right) von Mises stress at buckling load performed through SolidWorks Simulation FEA nonlinear analysis.

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Key Findings:

- Force requirements were significantly reduced by pre-buckling.
- Simulation data aligned closely with experimental results, highlighting the efficiency of pre-stressing materials.

Student Feedback on Design Projects

Survey Results

A survey was conducted after students completed the project and the overall feedback was positive.

Figure 20 illustrates the average scores from a survey that evaluated four aspects of a project on a 5-point Likert scale. The scale ranges from: **1**: Strongly Disagree to **5**: Strongly Agree

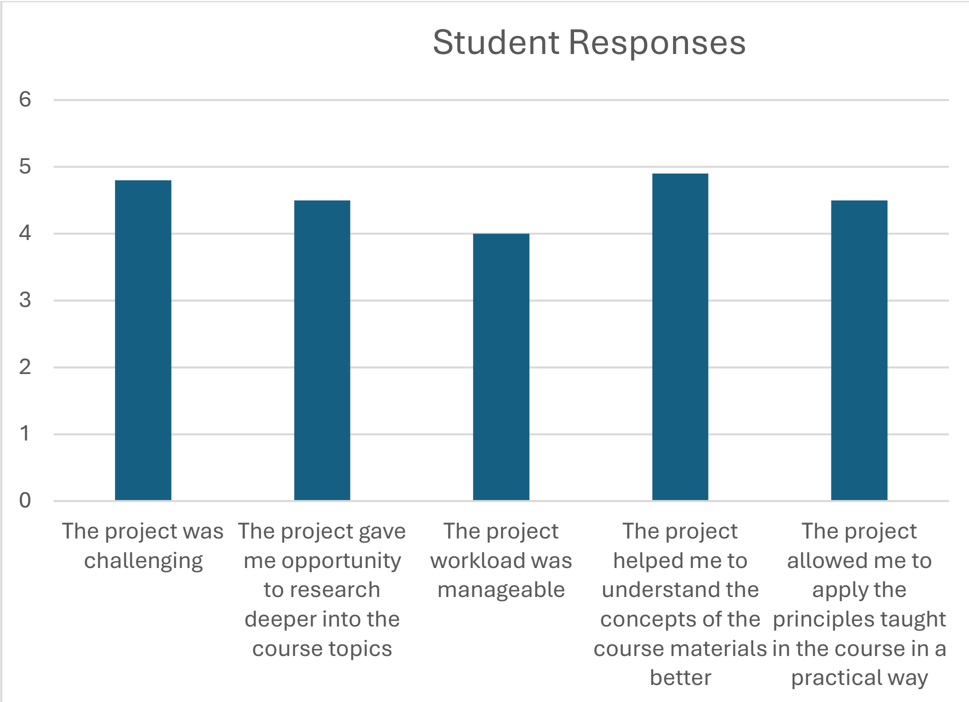

Figure 20: illustrates the average scores from a survey

This data represents feedback ratings about a project, with four different aspects of the project being evaluated. Each statement reflects a specific characteristic of the project, and the corresponding numerical values represent average ratings, likely on a scale from 1 (lowest) to 5 (highest).

Overall, the feedback is overwhelmingly positive, with high ratings across all aspects. The **highest-rated aspect** (5.0) is the project's ability to allow practical application of course principles, showing that this was its standout feature. The **lowest-rated aspect** (4.0) is workload manageability, suggesting this is an area that could benefit from improvement to enhance participant experience further. he project was particularly effective at deepening understanding (4.9) and enabling research into course topics (4.5). These projects underscore the importance of experiential learning in engineering, fostering technical skills and professional growth.

What Did students Like Most About The design projects?

Survey results indicate that 90 % of students found the project beneficial. Here are some of their comments:

- *"We were able to apply different equations and theories learned in lecture classes."*
- *"The course incorporated project-based learning, though it could benefit from referencing more relevant literature in this area."*
- *"I really enjoyed the open-ended nature of the design project and the collaborative lab reports."*
- *"The final design project was my favorite part, as it allowed us to explore course-related topics that aligned with our own interests."*
- *"The projects encouraged critical thinking about the labs and their real-world applications."*
- *"This course fostered an environment where student input was valued and expectations were clearly communicated."*
- *"It was a very hands-on course with engaging lab and design project experiences."*
- *"The design project was a highlight of the course."*
- *"The course was extremely helpful in understanding the theory behind the labs and LabVIEW."*
- *"The rigorous workload, combined with the instructor's detailed feedback and high expectations, greatly enhanced my technical writing skills."*

Suggestions for Course Improvement:

- *"Allow more time for students to explore their design projects freely."*

Advice for Future Students:

- *"Be prepared to put in the work and embrace hands-on learning."*
- *"Start thinking about design project ideas at the beginning of the semester."*

Learning Outcomes

Survey results indicate that 90% of students found the project beneficial. Key highlights include:

- Hands-On Application: Projects enhanced the practical application of classroom principles.
- Problem-Solving Skills: Open-ended challenges encouraged critical thinking and independent learning.

- Teamwork: Collaborative work fostered communication and leadership skills.
- Real-World Relevance: Exposure to industry-standard tools and workflows prepared students for professional roles.

Challenges & Solutions

1. Balancing Guidance and Independence: Structured check-ins ensured students received support without stifling creativity.
2. Realistic Scope: Clearly defined objectives and milestones helped students manage project complexity.
3. Resource Accessibility: Efficient scheduling and supplementary tutorials mitigated equipment and software limitations.
4. Group Dynamics: Peer evaluations and regular check-ins promoted accountability and collaboration.
5. Comprehensive Documentation: Emphasizing analysis and reporting ensured depth in students' work.

Conclusion

The Mechanics Laboratory course demonstrates the effectiveness of experiential learning in engineering education. Design projects bridge theoretical and practical knowledge, equipping students with technical and professional skills essential for career success. By addressing challenges and incorporating student feedback, the course continually evolves to enhance its impact on engineering education.

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