Weigh Dr. Lyons: An Application of Problem-Based Learning

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Abstract
A laboratory project is described that was developed for a mechanical engineering measurements and instrumentation course. Each student designs, constructs, calibrates and uses a strain gage based load cell to weigh the instructor. The project takes about three weeks to complete. Besides learning how strain gages work, each student significantly improves his or her ability to design experiments and practice mechanical engineering.

Introduction

In problem-based learning, students have the primary responsibility for their learning. The instructor serves as a resource or tutor, guiding the students in their problem solving efforts. Intended outcomes are increased student motivation and confidence, which lead to improved learning in the classroom and beyond. This paper discusses the implementation of problem-based learning strategies in a laboratory course called EMCH 361 - Measurements and Instrumentation. This is the first engineering laboratory course for mechanical engineers at the University of South Carolina.

The laboratory experience of many of our students prior to taking the measurements lab is restricted to cook-book style science experiments with fill-in-the-blank laboratory reports. These students are not prepared for an engineering experience where they must design, conduct and report upon their own experiments. Therefore, a scaffolding approach is used throughout the semester where the students are given increasing responsibility for developing experimental procedures and data analysis formats in successive experiments. For the final laboratory project in the course, the students must design, construct, calibrate and use a strain-gage based load cell. The load cell must accurately measure the weight of the instructor. A representative finished product is shown in Figure 1.

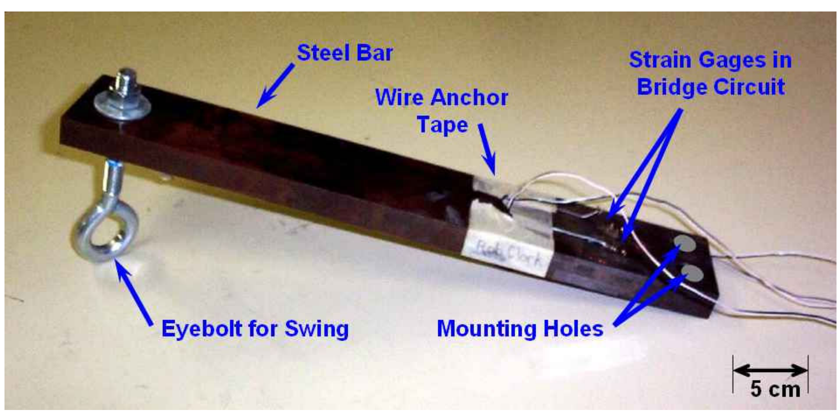

Figure 1. Typical load cell designed and constructed by a mechanical engineering student to weigh Dr. Lyons.

Why Weigh Dr. Lyons?

For a number of years in EMCH 361, students have applied strain gages to Coke cans to measure the change in strain when the can is opened. The pressure in the can before opening was then calculated from the measured strains in the longitudinal and transverse directions. The lab was interesting but became stale after years of use. Therefore, a new experiment to introduce students to strain gages was desired.

In an attempt to connect the new laboratory experiment as closely as possible to reality, we decided to develop an experiment that used strain gages in the construction of load cells. Descriptions of experiments were found in the literature where students constructed load cells by applying strain gages to pre-fabricated beams [1, 2]. We considered such an experiment because it could be easily implemented in one 3-hour laboratory session. However, it we also wanted to directly address the design component of ABET's Engineering Criterion 3(b) *an ability to design and conduct experiments, as well as to analyze and interpret data.* Therefore, we decided to extend the strain lab into a multi-week project for students to design, construct, instrument, calibrate and use their own load cell. Descriptions of experiments where students designed and constructed their own load cells were also found in the literature [3, 4, 5]. These measured forces in the range of only several pounds. We considered replicating one of these labs, because if a student's load cell failed, little damage would be done to the laboratory. However, we also wanted to make the consequences of load cell failure more severe so that students would feel some of the pressure that exists when practicing engineering in the real world. Therefore, we decided that the student's load cells must weigh the instructor as he or she sat in a swing suspended from a hook in the beam. If a load cell failed, the instructor would fall several feet to the floor and bruise his backside.

The Assignment

The students are introduced to the load cell design project in a lecture period before going into the lab. They are given a laboratory handout similar to that included in Appendix A. There are only four steps to the laboratory procedure on the handout: (1) Design the load cell, (2) Construct the load cell, (3) Calibrate the load cell, and (4) Weigh Dr. Lyons. The handout points out that the student's grade is based 10% on a design proposal and 90% on a final written report. However, they are told that if their load cell breaks and Dr. Lyons falls to the floor, they will fail the course. If students protest that this penalty is too harsh, the instructor tells them with a smile that he has complete confidence in their ability to succeed. However, if they can't design a static structure to support his weight, then they probably shouldn't be a mechanical engineer anyway.

As seen in Appendix A, the handout instructs the students to use a cantilever beam design for their load cell; it includes some details required to mount the load cell to the test stand in the laboratory. One detail that is missing is the allowable beam thickness. This is not mentioned to the students and they must discover that they need it, then measure it themselves. Each student is also given an eyebolt from which the instructor's swing will hang. They are responsible for finishing the design, including specification of beam material length, width and thickness, number and location of the strain gages, etc. The load cells must be designed with a factor of safety of at least 2, but have the largest sensitivity (strain/force ratio) possible. This illustrates to the students the need to make compromises during design, because a load cell with a large factor of safety would also be stiff and hence have a low sensitivity. The laboratory handout outlines instructions for the contents of the design proposal, which includes an executive summary, calculations and dimensioned shop drawings. It also includes the requirements for their final project report, which is a typical formal laboratory report.

Week One Activities

The laboratory room is open for the students during the first week so they may inspect and analyze the load cell mounting frame, the strain gages available to choose from and the strain measurement instrumentation. The instructor also meets with the students during regularly scheduled lecture periods, but only to respond to student questions. For example, questions about how to choose the number of strain gages lead to a good opportunity to discuss the Wheatstone bridge circuit and bridge factor equations.

At the end of the week, the students present their designs to the instructor and a technician in the machine shop for review and approval. Suggestions are offered to make the designs easier to manufacture. If a beam is obviously over- or under-sized, the instructor will suggest that students recheck their work. He does not, however, check the students' calculations for errors, despite their desire for this to occur. Continually showing confidence in the students helps build their self reliance. After the shop session, materials are purchased by the machine shop technician for the student's designs. It is important to note that the students have the option to acquire their own materials, but are limited to those available at a local distributor if they want the university to procure them. It is helpful to schedule the project so that student holidays (e.g. fall or spring break) occur after the shop session, giving the technician more time to procure the materials needed.

Week Two Activities

Laboratory sessions during the second week of the project occur in the machine shop. The students rough cut their beams with a band saw then lay out their designs on the blanks. They use a facing mill, drill press and file to complete their load cells. Calipers and metal rules are used to measure the load cell dimensions and mounting hole positions. For many students, this is the first opportunity to operate machine tools and gain first-hand experience with machine tool capabilities and shop tolerances. They are sometimes surprised that their finished product doesn't match the design specification even though their layout was precise. It has been observed that students who have previously worked in a shop mentor their less experienced colleagues. The opportunity for peer coaching is a valuable but unplanned benefit of this project.

Week Three Activities

The third and final week of laboratory activity is spent applying the strain gages (e.g., Measurements Group CEA-13-240UZ-120), calibrating the load cell, and weighing the instructor. A cantilever beam can use one, two or four strain gages in the bridge circuit. When only one gage on the top of the beam is used the strain measured is mainly the desired bending strain but also includes axial and twisting components. When two gages is applied (one on top and one to the bottom) and the bridge circuit is wired correctly, axial strains induced due to large-scale beam deflection can be eliminated from the measurements, but errors due to twisting remain. The use of four gages (two on top and two on bottom) can eliminate the errors due to both axial and twisting deformation. The students learn this during the first week design stage of the project, and almost all of them choose to use four gages for increased accuracy. However, in the third week laboratory session they experience the consequences of their design decision. The mounting of application of strain gages requires meticulous care and patience in order to get good results. The novice student takes 2 to 6 hours to get four good gage placements. Here, they experience first hand the need to balance the need for precision with the cost of achieving it.

Once construction is completed, the students mount their load cells in a frame, as shown in Figure 2. The strain gages are connected to a strain indicator (e.g., Measurements Group P3500). A stack of up to eight 89 N (20 lb) weights are stacked on the swing that is suspended from the eye hook in the load cell, and the strain from the gages is recorded along with the applied force. Each student repeats this calibration procedure at least twice and consequently observes the phenomena of load cell drift due to small changes in mounting geometry after loading. The final step of this three week project takes less than a minute as the instructor sits on the swing and the strain he creates in the student's load cell is recorded. This event is shown in Figure 3. For personal reasons, typical results will not be presented here.

Figure 2. A student calibrates his load cell with a stack of twenty pound weights.

Figure 3. A student records the strain that Dr. Lyons creates in their load cell.

Discussion

An instructive aspect of the project is that students must determine and use three different calibration factors to determine the weight of the instructor (a calibration factor relates the strain measurement to the applied force). The first calibration factor is calculated through solid mechanics using the beam dimensions on the student's design proposal dimensions. To determine the second calibration factor, the students have to measure these dimensions after they have fabricated their load cell, then recalculate the calibration factor using solid mechanics. The third calibration factor is determined by hanging known weights on the load cell, measuring the induced strain, and performing a linear regression to determine the force-strain relationship. The range of known weights is deliberately less than the weight of the instructor so that the students cannot interpolate their data to find his weight; they must extrapolate beyond the calibration range, thereby increasing the possibility of errors.

The three calibration factors are invariably different, giving three possible values for the instructor's weight. Students also must calculate the uncertainty in each weight value. They are also required to report what they think is the instructor's real weight. Here they must apply engineering judgment, because the uncertainty associated with the design dimension-based calibration factor is zero. Uncertainties of the experimental values must be calculated by propagation of errors from measurements made. Based on the accuracies of the measurement devices used, the uncertainties of the two experimentally determined calibration factors are comparable. The students have to justify their conclusion of what the instructor's weight really is based on the numerical uncertainty in the calculated values as well as the reality of the situation. This is the first opportunity for many students to make such a judgment about the value of data and ideas.

Assessment

The effects of problem based learning in this course have been assessed with a pre/post survey. The pre-survey is administered on the first day of class, and asks students to rate their level of competency in fifteen skill areas. The post-survey is administered on the last day, and asks students to again rate their level of competency in the same skill areas. This method is preferred over asking students to self-rate changes in their level of learning. Students write the last four digits of their social security number on their survey, which allows the surveys of students who dropped the class, or who only filled out the post survey for some reason, to be discarded prior to data analysis. The results for the five items that changed the most over the course of a semester are shown in Figure 4.

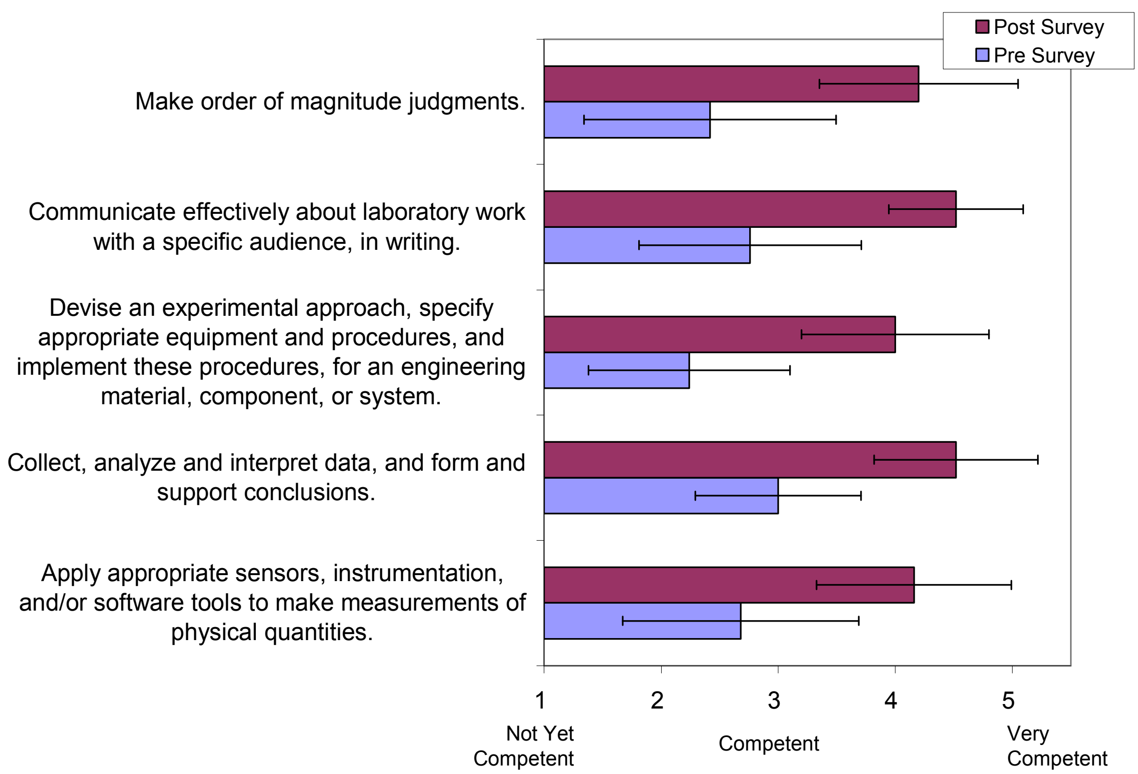

Figure 4. Average pre- and post-survey results for the five competencies with the greatest change in student perception of their abilities. Error bars represent one standard deviation.

Comparison of pre- and post-course survey results indicate that the problem based learning approach does address higher-level learning outcomes such as devising an experimental approach, specifying appropriate equipment and procedures, and implementing these procedures. It is important to note that other experiments performed by the students during the course are important in developing the their abilities to design the load cell experiment. The survey results presented here reflect the changes in student attitudes due to all of these experiences, the load cell project being the capstone event. These results do provide encouragement for a purposely designed research program into the cognitive and affective affects of this experience. In particular, the pre/post surveys do not assess the look of accomplishment (or perhaps relief) on a student's face when the instructor hangs from his or her load cell, and it doesn't break.

Conclusion

Throughout the process, the students are forced to function just beyond their level of comfort. They have to struggle to determine what data they need to make an effective design. They are challenged to machine an object that meets their design requirements. They must be patient and painstakingly meticulous when applying their strain gages. They must have confidence in themselves when the instructor finally approaches their load cell and begins to apply the full of his weight to their design. It is suggested that these outcomes are far more important than the knowledge of how strain gages work that is also gained.

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Biographical Information

Dr. Lyons is an Associate Professor of Mechanical Engineering at the University of South Carolina and the Director of the South Carolina Center for Engineering and Computing Education. He teaches laboratory, design, and materials science to undergraduates, graduate students and K-12 teachers. He researches engineering education, plastics and composites.

Appendix A

Load Cell Design and Build Project Handout

EMCH 361 – Measurements and Instrumentation

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Objective

The objective of this project is to design, construct, calibrate and use a strain-gage based load cell. The load cell must accurately measure the weight of the instructor.

Procedures	**Grade Basis:**	**Due Dates**:
1. Design the load cell. 2. Construct the load cell. 3. Calibrate the load cell. 4. Weigh Dr. Lyons.	10% Design Proposal 90% Final Report	Design Proposal: 3/7/03 Final Report: 4/11/03

Design Constraints

The beam must be designed to fit a fixture with the bolt pattern as shown in Figure 1. An eye-bolt will be provided from which the load will be suspended. Attachment bolts will be available in the lab. The beam must not deform permanently upon application of the test load. The following design considerations are left to the student: (a) Material, (b) Cross sectional design, and (c) Length (but length cannot exceed 20"). If you want the university to purchase the materials for you, then they must be available from http://www.metalsupermarkets.com/.

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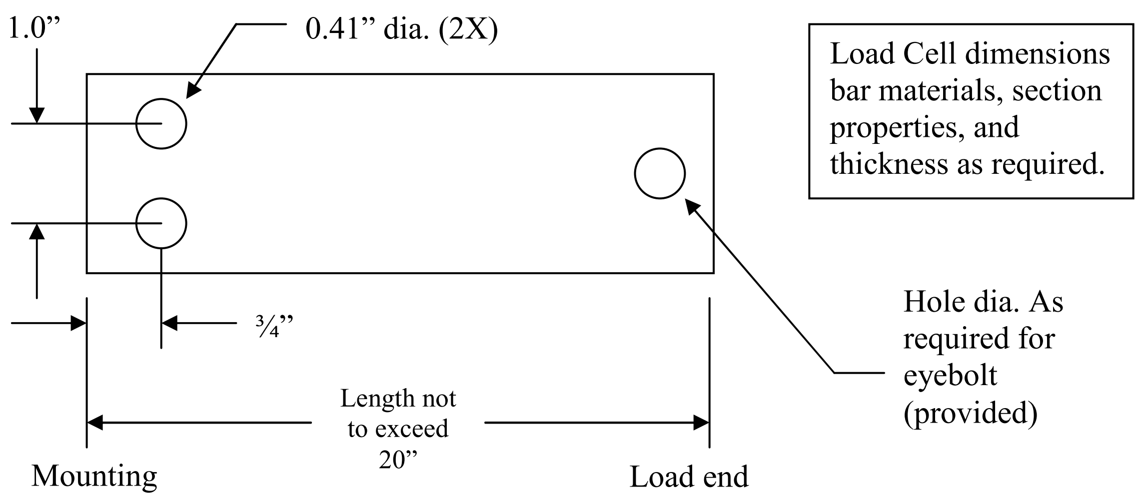

Figure 1. Load cell beam connection dimensions.

Design Proposal Report Requirements

This report should include the following sections and information:

1. Cover sheet with Title, Name, Date, and a 200-500 word Executive Summary.
2. Calculations and results for the predicted design factor of safety (n),

$$n = \frac{\sigma_y}{\sigma_{max}} \qquad (1)$$

where σ_{max} is the maximum stress in the load cell and σ_y is the yield stress of the proposed construction material. The safety factor should be more than 2.

3. Calculations and results for the design calibration factor,

$$C_d = \frac{F}{\varepsilon} \tag{2}$$

where F is the applied force and ε is the strain at the location of the strain gage(s).

4. 2 copies of a dimensioned drawing showing the placement and sizes of all features and the intended placement of the strain gage. Indicate the construction material on the drawing.

Final Project Report Requirements

Your report must include the following sections:

1. **Cover Sheet**. Include title, name, date and a 100-250 word Abstract that summarizes the work and reports the significant findings.
2. **Introduction**. Present the context and objective of this project. Describe how strain gages work and how they are used in load cells.
3. **Analysis**. Present the theory and equations for your load cell factor of safety *n* and your load cell design calibration factor C_d . Present a labeled and dimensioned schematic of your load cell, and report the calculated values of *n* and C_d .
4. **Procedures.**
   Construction - Describe the process of designing and constructing your load cell, including the types and locations of strain gages you used. Describe the process of applying the strain gages. Measure all of the actual dimensions of the load cell and report these in a table. Use these measurements to calculate the load cell calibration factor based on geometry:
   $$C_g = \frac{F}{\varepsilon} \tag{2}$$
   Calculate and report the uncertainty in C_g (show the equations and data used).
   Calibration and Testing - Describe the set-up and process for calibrating your load cell. Describe all of the instrumentation used in the calibration process and the instrument uncertainties. Describe the procedure for weighing Dr. Lyons.
5. **Results and Discussion**
   Calibration Results. Present and discuss the calibration results. The experimental calibration data should be graphed with along with a linear trend line. The slope of the trend line should be the load cell calibration factor based on strain:
   $$C_s = \frac{F}{\varepsilon} \tag{3}$$
   Calculate and report the uncertainty in C_s (show the equations and data used).
   Testing Results. Calculate and report the weight of Dr. Lyons using all three calibration factors C_d, C_s and C_g. Calculate and report the uncertainty in each weight prediction using Kline-McClintock analyses (show work). Report this data in a table. Discuss the results, compare them to each other with respect to the uncertainties, account for differences and/or errors. Report what you think is Dr. Lyons' real weight and justify that conclusion.
6. **Conclusions**. Summarize what you did. Make qualitative and quantitative conclusions.
7. **References.** Cite all sources of information used.