Enhancing Combined Stress Laboratory Learning Opportunities

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Abstract:
Combined stress theory coupled with laboratory practice has improved student comprehension in both a sophomore-level mechanics of materials and an upper-level experimental mechanics course. The Combined Stress lecture has traditionally developed the theory from free body diagram through beam deflection, with related homework problems providing analytical practice. Similarly, the Combined Stress laboratory has traditionally provided students an opportunity to experimentally and analytically verify and validate the combined stress theory. Good correlation between theoretical and experimental results was frequently obtained through the utilization of a carefully machined C-Clamp with strain gage instrumentation. However, the twist method of introducing axial and bending loads to the inside and outside surfaces of the beam portion of the C-Clamp instrumented strain gages limited both the accuracy and the amount of data that could be collected within a standard 110-minute laboratory session.

Recent Combined Stress laboratory upgrades have included introducing a load cell transducer, 3D modeling, Finite Element Analysis (FEA) and utilizing data acquisition (DAQ) hardware and software. The voltage output of the load cell can be directly correlated to the clamping force and provides a useful, new experimental baseline result. The FEA analysis outputs, at various load levels, provide a new analytical baseline result. Together, these new experimental and analytical baseline results have provided students significant new learning opportunities as they compare and contrast these results with their traditional analyses of the experimentally-obtained strain measurements. The DAQ has provided much improved granularity of test data in roughly the same timeframe with increased repeatability. Together, these upgrades have facilitated increased understanding of combined stress theory, introduced modern experimental methods in both lecture and laboratory, provided the students two new baselines against which to compare and contrast, given students a finer granularity data set upon which to base their analyses, and enhanced student experiences with technical report writing. This paper includes both an overview of the Combined Stress theory, analysis techniques, and traditional laboratory procedures and details of the success of the Combined Stress laboratory upgrade, operation, and outputs.

Introduction:
Magill designed and implemented a combined bending and axial loading experimental mechanics laboratory using a C-Clamp that produced exceptional correlation between theoretical and empirical results. Improving on this laboratory was difficult as the lab was simple and had few drawbacks. Coyle, et al presented an innovative derivative of Magill’s combined stress experiment utilizing a hacksaw instead of a C-Clamp. There are few drawbacks with Magill’s present C-Clamp laboratory. The upgrades of the combined stress laboratory to include data acquisition (DAQ), provide other analysis alternatives, introduce strain gage rosettes, and address some minor drawbacks were the primary motivations for the applied research presented in this paper.
History of Combined Stress Experiment:
Magill custom-designed a C-Clamp and laid out the theoretical derivation of the clamping force in parametric terms, as shown in Figure 1.

Denton\textsuperscript{3}, et al incorporate this combined stress experiment in the sophomore-level mechanics course laboratory manual. To determine $F_T$ and $F_C$, students were required to determine the tensile modulus, $E$, tensile and compressive strains, $\varepsilon_T$ and $\varepsilon_C$, cross-sectional area, $A$, area moment of inertia, $I$, distance from force vector center to neutral axis, $d$, and distances from the neutral axis to the tensile and compressive edges, $c_T$ and $c_C$. Magill was able to demonstrate an outstanding correlation of +/- 2% between $F_T$ and $F_C$ using the strain gage outputs and having the students twist the C-Clamp shaft through ¼ turn increments.

Upgrades to the Combined Stress Laboratory were performed in two courses in the mechanics area: MET 211 Applied Strength of Materials\textsuperscript{4} and MET 311, Experimental Strength of Materials\textsuperscript{5}. These upgrades were performed to allow enhanced learning opportunities in data acquisition, data analysis, strain gage rosettes, and to address some minor drawbacks with the present lab.

Upgrade Number 1: Integrate a Load Cell
This upgrade involved the integration of a load cell to both the MET 211 and MET 311 combined stress laboratories. The purpose of the load cell was to provide an experimental baseline for the clamping force. The clamping forces that are indicated by the tensile-side and compressive-side strain gage readings can now be compared to this baseline force, in addition to being compared with each other. Given the low clamping load allowed (e.g. maximum of 150 lbf) a 500 lbf load cell was selected and is shown in Figure 2 below.
The load cell addition required another P3500™ from Vishay Measurement Group be added to the traditional two each P3500’s, as shown below in Figure 3.
The wiring diagram for the three transducers is shown below in Figure 4.

![Wiring diagram of three transducers](image)

**Figure 4: Wiring diagram and picture of the three transducers connection with P3500™'s**

**Upgrade Number 2: Integrate Data Acquisition (DAQ)**

Most of the mechanical engineering technology department’s mechanics laboratories are being upgraded to industry-standard LabVIEW™ software. The DAQ upgrade involves generating a new LabVIEW™ VI with an associated diagram. For MET 211, the DAQ entailed only three inputs: Tensile Strain, Compressive Strain, and Load as shown in Figure 5 below. For MET 311, the DAQ upgrade required seven inputs: Tensile Rosette with three gages, Compressive Rosette with three gages, and Load as shown in Figure 6 below.
The difficulty of rosette mounting on the narrow area is shown in Figure 7 below. The purpose of integrating the rosette into the MET 311 combined stress experiment was to reinforce the lecture.
material on rosettes. Unfortunately, due to the narrow cross-section of the neck of the C-Clamp, the rosette could only be mounted along the major strain axis with the result that the outer strain gages had the same reading.

Figure 7: Area for mounting the tensile strain gage rosette. The compressive strain gage rosette was mounted in a tighter area than shown above.

Details of the 3-input and 7-input DAQ for the combined stress laboratory are included in the following pictures. The wiring diagram from the P3500™’s to the DAQ is shown in Figure 8.

Figure 8: Wiring diagram of 3-input DAQ
The Analog Input Configuration screens from LabVIEW™ are shown in Figure 9 below.

Figure 9: Analog Input Configuration screens from LabVIEW for the Load Cell, Compressive Strain Gage, and the Tensile Strain Gage.
The LabVIEW™ diagram for the 3-input and 7-input DAQ's are shown in Figure 10 below.

Figure 10: 3-input and 7-input DAQ LabVIEW™ diagrams
Figure 11 shows several lab set-ups with the enhanced combined stress laboratory.

With the addition of the load cell and the DAQ (both 3-input and 7-input), the laboratory teams performed as well as prior to adding the load cell and DAQ based on the quality of data available from previous semesters this laboratory was given. The data reduction was principally the same with the extra, measured parameter (e.g. Load) helping give the students increased understanding of the principals of combined stress. One advantage of adding the load cell and DAQ was that during a given LabVIEW run, multiple passes of tension and compression could be accomplished easily. These multiple passes went into a spreadsheet where the goal was for regression analysis to help smooth out noise and hysteresis. Similar accuracy was obtained, however, enhanced learned occurred with the discovery that there was no time parameter in the strain and load data,
allowing these multiple runs to occur within LabVIEW™. Plots of the raw strain gage versus load data are shown below with the regression line in Figure 12.

Figure 12: Raw data plots from combined stress laboratory

The MET311 laboratory modeled the Magill C-Clamp and performed finite element analysis (FEA) on the clamp at a given load. The strain plots from the FEA at given loads were compared with the measure strain and reported in a class presentation. The solid model is shown in Figure 13 below along with the FEA model in Figure 14.

Figure 13: Solid model of Magill C-Clamp
Conclusions:
Enhancements to a pre-existing combined stress laboratory resulted in expanded learning opportunities for both lower-division and upper-division mechanical engineering technology mechanics of materials students. These enhancements were the addition of a load cell to monitor primary clamping force and the integration of DAQ in both 3-input and 7-input configurations. The upper division students additionally solid modeled and analyzed the Magill C-Clamp using finite element procedures and contrasted these results with the strain readings obtained experimentally.

An additional enhancement is planned for the combined stress laboratory. In one case, the students will fabricate a photoelastic model of the Magill C-Clamp using stereolithography techniques and testing the stress values experimentally using photoelastic means. In another, they will design an improved clamp and work with the metal casting class to fabricate a prototype for testing.

Figure 14: FEA of Magill C-Clamp design showing linear and non-linear stress regions
Bibliography:
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   http://www.tech.purdue.edu/met/courses/met211/
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Biography:

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Professor Szaroleetta is an assistant professor of mechanical engineering technology at Purdue University. A member of ASEE, he has 18 years industry experience in engineering and project management positions, with 12 awarded patents. He has 6 years university teaching experience, where his current applied research interests are rapid product design engineering, experimental mechanics laboratory automation, and optimization utilizing genetic algorithms.