Recommended Format for Mechanics of Solids Laboratory Reports

A. Title page
   (a) Lab title
   (b) Names of participant(s)
   (c) Date of experiment
   (d) Date submitted

B. Introduction
   In one short paragraph, summarize the objective of the experiment (what we wish to show or prove).

C. Apparatus
   In one short paragraph, summarize the instrumentation, the experimental setup and the general procedure used for this experiment.

D. Results
   In this section, include the reduced data in the following form:
   (a) Figures (graphs and drawings)
      i) Graphs
         - figure number
         - title
         - label axis with appropriate parameters
         - intelligent choices of numerical divisions
         - units when required
         - include legend or label with arrows if more than one set of data is presented on the same graph (include the location of tabulated numbers)
         - plot the experimental data points by marker symbols (do not connect the markers, use best fitting polynomials or other more appropriate theoretical equations to show trends drawn in continuous lines)
      ii) Drawings
         - figure number
         - title
   (b) Tables (typed or neatly printed)
      - table number
      - title
      - columns of reduced data with the following:
         * headings
         * units if required
         * lines to separate columns and headings
E. **Discussion**

In paragraph form, clearly and concisely discuss the results, reference graphs and tabulated data presented in the previous section. Also in this section, answer all the questions contained within the lab write-up in words and by references to the results. State trends and how these trends compare with established theory. Reference other sources to show that the trend in the data is correct or in error. Discuss possible sources of error in the experiment.

F. **Conclusion**

In one or two paragraphs, briefly summarize the main points from the discussion section and show how they address the main objective put forth in the introduction section (leave no question unanswered).

G. **Appendix A: Raw Data** (include typed cover page with those words)

Include in this section the original raw data sheet. It should be neat and labeled with units.

H. **Appendix B: Sample Calculations** (typed cover page with those words)

In this section, include an annotated explanation of how and in what order the raw data was reduced to produce the data in the Results Section. Include in this section:

- equations
- reasons and assumptions made that enables one to use the equations
- define each term in the equation and any specific units that must be used
- provide one sample calculation with numbers (give the source of the data) to show that units cancel and say where the remainder of the results can be found (e.g., see Table 1)
- provide any tables with intermediate calculations or results (i.e., unit conversions, etc.)
- present results in units appropriate for the parameter (in psi, µin/in, etc.)

NOTE: The use of proper English must be observed at all times. For further information on technical report writing and format, consult Chapter 15 of Experimental Methods for Engineers by J. P. Holman, 5th edition. 1989.
EXPERIMENT #1 (no report)

DISPLACEMENT AND STRAIN MEASUREMENTS IN A CANTILEVER BEAM

Objective: To become familiar with measuring and recording static displacements and strains with virtual instrumentation, to practice statistical data evaluation procedures.

Apparatus: A steel cantilever beam (see Data Sheet CB-2), SC-2043 SG Strain Gage Signal Conditioner, a digital dial gage, LabView Virtual Instrumentation.

Experimental Steps:

1. Connect strain gages 1, 2, 7, 5, 6, and 9 to channels 0 through 5 of the strain gage signal conditioner in this order. Set up the digital dial gage to measure the end displacement of the beam and connect it to the computer via the serial port.

2. Run the beam.exe virtual instrument. Set the six gage factors, zero the indicators without load, and save the data. Load the beam in 1-pound steps up to 20 pounds and save the six strains and the end displacement at each load (the virtual instrument will prompt you to the next load in each step). Repeat the loading three more times to obtain a total of four sets of data.

Data Evaluation:

3. Plot the measured and theoretically predicted end displacements as a function of the load.

4. Plot the measured and theoretically predicted magnitudes of the six strains as functions of the load (gages 7 and 9 are in compression).

5. Evaluate the data.

   a) Based on the four measurements, what is the average value and standard deviation of the end displacement at \( P = 2 \) lbs and \( P = 20 \) lbs? Is there a significant difference between the two standard deviations and why?

   b) Calculate and plot the average end displacement \( \bar{v} \) as a function of the load \( P \)? Is the average end displacement a linear function of the load? Fit the data with a third-order polynomial of the form

      \[ \bar{v} = a_0 + a_1 P + a_2 P^2 + a_3 P^3 \]

   and list the best fitting parameters \( a_n \), where \( n = 0, 1, 2, 3 \) (include this best fitting polynomial in the plot).

   c) Use the previously determined \( a_1 \) value to estimate Young's modulus.

   d) Based on the four measurements, what is the average value and standard deviation of the strain at Gage 1 at \( P = 2 \) lbs and \( P = 20 \) lbs? Is there a significant difference between the two standard deviations and why?
e) Based on the twelve measurements, what is the average value and standard deviation of the strains at Gages 1, 2 and 7 (change the sign of strain #7 for consistency) at $P = 20\text{ lbs}$? Is there a significant difference between these values and the corresponding ones calculated for Gage 1 only?

f) Calculate and plot the average strain $\bar{\varepsilon}$ at Gages 1, 2 and 7 (change the sign of strain #7 for consistency) as a function of the load $P$? Is this average strain a linear function of the load? Fit the data with a third-order polynomial of the form $\bar{\varepsilon} = b_0 + b_1 P + b_2 P^2 + b_3 P^3$ and list the best fitting parameters $b_n$, where $n = 0, 1, 2, 3$ (include this best fitting polynomial in the plot). Use $b_1$ to estimate Young's modulus.

g) Repeat steps e and f for Gages 5, 6 and 9 (change the sign of strain #9 for consistency).

h) What are the relative errors of the experimentally determined three Young's moduli (steps c, f, and g) with respect to the tabulated nominal value? Are the experimentally determined Young's moduli closer to each other than to the nominal value?

Steel Cantilever Beam
Data Sheet CB-2

Beam:  Steel, $E = 30e6$ psi (nominal)
Strain gages:  1, 2, 6, 7, 9 - A5, R=120Ω, F=1.97
3, 4 - AX5, R=120Ω, F=2.03
5 - EA-13, R=120Ω, F=2.05
8 - A5-S6, R=120Ω, F=1.98
EXPERIMENT #2 (report)

USE OF ROSETTE GAGES ON A PLATE IN BENDING

Object: To become familiar with the use of rosette strain gages for finding complete strain data at a point in a structure such as a flat plate. Also become familiar with the techniques of analyzing rosette test data.

References: The Strain Gage Primer - Perry and Lissner, pp. 133-146

Apparatus: A brass cantilever plate with two rosette gages mounted on it; a rectangular (45-degree) rosette and a delta (60-degree) rosette (R 120 Ω, \( F = 2.1 \)), SC-2043-SG Eight-Channel Strain Gauge Signal Conditioning Board, VirtualBench Digital MultiMeter, rosette.vi dedicated LabView program.

Experimental Steps:
1. Record the dimensions of the cantilever plate, the location and geometry of the two rosette strain gages and the location of the load points. Show these on a sketch along with the x-y coordinate system.
2. Connect gages 0 through 5 to Channels 0 through 5 on the Signal Conditioning Board and indicate the channel numbers on the schematic diagram.
3. Configure the VirtualBench Digital MultiMeter to measure Channel 3 at slow sampling rate in the 100 mV DC range. Balance the bridge if the reading in the unloaded state is in excess of ±50 mV.
4. Null the multimeter, load the plate at its center by 15 lbs, and record the reading. Repeat this procedure 5 times and calculate the average.
5. Change the channel under "General Setting" of the DMM to Channel 0. Repeat step 4 by using the math function. Instead of reading \( U_m \) directly from the display in mV or \( \mu V \) and then multiplying it by \( M \) to get the strain in \( \mu in/in \), use the Math function to calibrate the DMM to 1 \( \mu in/in \) per 1 \( \mu V \) display sensitivity (for \( M \), see step 8 in Data Reduction and Analysis).
6. Repeat step 5 on channels 0 and 3 by loading the plate by a 15-pound load on the left and right sides.
7. Run the rosette.vi dedicated LabView program. Place a 15-pound load on the plate at the center location. Record the strain meter readings five times for each gage and average the results to increase the accuracy.

Data Reduction and Analysis:
8. Determine the average strain of Gage 3 from the voltage measured in step 4. 
\[ \varepsilon = U_m \times M, \quad \text{where} \quad M = -4/(U_o \times G \times F) \]. The excitation voltage is \( U_o = 2.5 \) V, the gage factor is \( F = 2.1 \) (the same for all gages), and the internal gain of the signal conditioning board is \( G = 10 \), so that \( M = -0.07619 \) [V^{-1}]. Compare this value to the average strain of Gage 0 from step 5. Explain the result of the comparison.
9. Compare the four averaged strains measured in step 6. Is the symmetry requirement satisfied?

10. Calculate the Cartesian strain components $\varepsilon_x$, $\varepsilon_y$, and $\gamma_{xy}$ from the measured normal strains for both locations from the average values from step 7 by adapting the stress transformation equations.

11. Calculate the principal strains $(\varepsilon_M, \varepsilon_m)$, the maximum shear strain $(\gamma_{\text{max}})$, and the orientation of the principal direction $(\theta_p)$ with respect to the $x$-direction for each rosette by Mohr's Circle or by the analytical forms of the strain transformation equations.

12. List the results of steps 10 and 11 in a table comparing the rectangular rosette to the delta rosette. Evaluate the differences between rosettes.

13. Sketch the plate and show the directions and magnitudes of $\varepsilon_M$ and $\varepsilon_m$ for each rosette (show both the magnitude and direction of angle $\theta_p$). Is symmetry at least approximately satisfied?
EXPERIMENT #3a (report)

TORQUE TRANSDUCER

Object: To study the theory of strain gage torque transducers and verify the theory experimentally.

References: The Strain Gage Primer - Perry and Lissner, pp. 203-206

Apparatus: A steel tube with 1.0" O.D. and \( t = 0.063" \) wall thickness, \( E = 26 \times 10^6 \) psi and \( \nu = 0.3 \) having type CEA-06-062UR-120 strain gages with a nominal resistance of 120 ohms and a gage factor of 2.05, an SC-2043-SG Eight-Channel Strain Gauge Signal Conditioning Board, VirtualBench Digital MultiMeter.

Experimental Steps:

1. Make a sketch of the experimental set-up showing tube and lever dimensions and the strain gage locations.
2. Arrange the four gages in a strain meter in such a manner as to measure torque and reject bending and axial force. Show a sketch of the circuit in the report.
3. \( \varepsilon_m = U_m \times M \), where \( M = -4/(U_o GF) \). The excitation voltage is \( U_o = 2.5 \) V, the gage factor is \( F = 2.05 \) for all four gages, and the internal gain of the signal conditioning board is \( G = 10 \), so that \( M = -0.07805 \) [V\(^{-1}\)]. Instead of reading \( U_m \) directly from the display in \( \mu V \) and then multiplying it by \( M \) to get the strain in \( \mu \text{in/in} \), use the Math function to calibrate the DMM to 1 \( \mu \text{in/in} \) per 1 \( \mu V \) display sensitivity. Balance the strain meter by zeroing the DMM.
4. Load the tube, using a torsional lever arm of 20" from the centerline of the tube, with 5, 10 and 15 pounds. Record the strain meter readings. Unload and check zero.

Data Reduction and Analysis:

5. Calculate the theoretical transducer constant \( K \).
6. Using the strain meter readings from step 4 and the transducer constant from step 4, calculate the experimental torques due to 5, 10, and 15 pounds.
7. Calculate the theoretical torques due to 5,10, and 15 pounds.
8. Construct a data table comparing experimental torques from step 6 with the theoretical torques from step 7. Show % of errors.
9. Comment on the rejection of bending and axial deformations.
10. Next, the transducer will be calibrated. Plot the theoretical torque (ordinate) versus the strain meter reading (abscissa) using the data of steps 4 and 7. From this graph determine an experimental transducer constant and compare to the theoretical transducer constant from step 5. Which transducer constant do you consider to be more accurate?
Derivation of Transducer Constant for the Torque Transducer Experiment

\begin{align*}
\tau_{xy} &= -\frac{T r_o}{J} = -\frac{T r_o}{2 \pi r_o^3 t} = -\frac{T}{2 \pi r_o^3 t} \\
\gamma_{xy} &= -\frac{\tau_{xy}}{G} = -\frac{T}{2 \pi r_o^2 t G} \\
\varepsilon_x &= \varepsilon_y = 0 \\
\varepsilon_N &= \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2} \cos 2\theta_N + \frac{\gamma_{xy}}{2} \sin 2\theta_N \tag{4}
\end{align*}

Substitute (2) and (3) into (4)

\[\varepsilon_N = \frac{\gamma_{xy}}{2} \sin 2\theta_N = -\frac{T}{4 \pi r_o^2 G} \sin 2\theta_N \tag{5}\]

\[\theta_N = -45^\circ \text{ (gages } N = 1 \text{ and } 3)\]

\[\varepsilon_{1,3} = \frac{T}{4 \pi r_o^2 t G} \tag{6}\]

\[\theta_N = 45^\circ \text{ (gages } N = 2 \text{ and } 4)\]

\[\varepsilon_{2,4} = -\frac{T}{4 \pi r_o^2 t G} \tag{7}\]
For the Wheatstone Bridge

\[ \varepsilon_m = \varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 = 2(\varepsilon_1 - \varepsilon_2) = 4\varepsilon_1 \]  \hspace{1cm} (8)

Substitute (6) into (8)

\[ \varepsilon_m = \frac{T}{\pi r_o^2 t G} \]  \hspace{1cm} (9)

\[ T = \pi r_o^2 t G \varepsilon_m = K \varepsilon_m \]  \hspace{1cm} (10)

Therefore, the transducer constant is

\[ K = \pi r_o^2 t G = \frac{\pi r_o^2 t E}{2(1 + \nu)} \]  \hspace{1cm} (11)
EXPERIMENT #3b (report)
MOMENT TRANSDUCER

Object: To study a strain gage transducer that measures the moment at an inaccessible location (such as at the root of a cantilever beam) and to verify the theory experimentally. Temperature stability is also investigated.

References: The Strain Gage Primer by Perry and Lissner, pp. 229-232. Course class notes.


Experimental Steps:

1. Set up a four-gage circuit on the CB2 of the SC-2043-SG Strain Gauge Signal Conditioning Board so that $\varepsilon_m = \beta \varepsilon_B - \varepsilon_A = \varepsilon_1 + \varepsilon_2 - \varepsilon_6 - \varepsilon_7$.

2. Calibrate the DMM to 1 $\mu$in/in per 1 $\mu$V display sensitivity. $\varepsilon_m = U_m \times M$, where $M = \frac{4}{(U_o G F)}$. The excitation voltage is $U_o = 2.5$ V, the gage factor is $F = 1.97$ for all four gages, and the internal gain of the signal conditioning board is $G = 10$, so that $M = 0.08122 \, [\text{V}^{-1}]$. Instead of reading $U_m$ directly from the display in $\mu$V and then multiplying it by $M$ to get the strain in $\mu$in/in, use the Math function (help: load the moment.set configuration file).

3. Load the beam with 5 pounds and obtain the meter reading. Increase the load to 10 pounds and then to 15 pounds and obtain the strain meter readings. Unload and check zero.

4. Repeat steps 2 and 3 on the Logger (help: load the stabilit.set configuration file). Record and print out the complete load cycle using the range of $\pm 1,000$ $\mu$in/in.

5. Change the range of the Logger to $\pm 100$ $\mu$in/in. Remove the load and place the heat lamp above the clamped left end of the beam at a distance of 8 inches and turn on the light for 10 seconds. Record and print out the complete heating cycle.
Data Reduction and Analysis:

6. Calculate the transducer constant $K$ for the four-gage bridge used in step 1.

7. From the data of steps 2 and 3 find the experimental moments $M_C$ for all three loads.

8. Include in your report the flow-chart recorded by Logger in step 4. Find the experimental moments for all three loads.

9. Construct a table comparing experimental moments from steps 7 and 8 with the theoretical moments and show % of errors.

10. Include in your report the flow-chart recorded by Logger in step 5. Explain the observed instability.
Derivation of Transducer Constant for the Moment Transducer (Torque Wrench)  

Experiment

Moment Transducer

If no loads are allowed between A and C, then the shear and the slope of the moment diagram is constant.

\[ M_C = 1.5 M_B - 0.5 M_A = \frac{EI}{h} (3\varepsilon_B - \varepsilon_A), \text{ where } I = bh^3/12 \]

If we can arrange the gages on the beam and in the Weatstone bridge such that the measured strain \( \varepsilon_m = 3\varepsilon_B - \varepsilon_A \), the moment at the root of the cantilever can be calculated from \( M_C = K\varepsilon_m \), where \( K = EI/h \) is a transducer constant.

The following circuit, using two top gages and one bottom gage at station B and one top gage at station A, gives \( \varepsilon_m = 3\varepsilon_B - \varepsilon_A \) and rejects other quantities such as axial force, torque, etc. However, it does not possess particularly good temperature compensation, because a longitudinal temperature gradient can cause the gage at station A to be uncompensated and a temperature gradient through the thickness can cause problems at station B.

\[ U_m = \frac{U_o G F}{4} (\varepsilon_1 + \varepsilon_2 - \varepsilon_6 - \varepsilon_7) = \frac{3\varepsilon_B - \varepsilon_A}{M} = \frac{\varepsilon_m}{M} \]
EXPERIMENT #4a (report)

ASYMMETRIC BENDING OF A CANTILEVER BEAM

Objective: To study the theory of asymmetric bending and to verify the theory experimentally.

Apparatus: A 36”-long aluminum cantilever beam made of 2”×2”×3/16” angle ($E=10^7$ psi, $I_{yy}=I_{zz}=0.256$ in$^4$, $I_{yz}=0.161$ in$^4$, $\bar{y} = \bar{z} = 0.56$ in), SC-2043 SG Strain Gage Signal Conditioner, Lab View Virtual Instrumentation.

Three strain gages, $F=2.07$, are located 34” from the tip of the beam and their locations on the beam cross section are: (a) bottom gage is 0.25” to the right of the vertical face of the angle, (b) the lower side strain gage is 0.875” above the bottom face of the angle and (c) the upper side strain gage is 1.5” above the bottom face of the angle.

Two digital dial gages are mounted at the tip to measure the horizontal and vertical displacements.

Experimental Steps:

1. Sketch the beam and locations of the load, strain and displacement gages.
2. Run the “asymmetric bending.exe” virtual instrument. Set the gage factors. Load the beam at the tip in 1-pound steps from 10 to 20 pounds. Save the strains in each gage and the two displacements at each load (the virtual instrument will prompt you to the next load in each step).
3. Repeat step 2 four more times to obtain a total of five sets of data.

Data evaluation and analysis:

4. Calculate the theoretical strains for the three strain gages and the theoretical values of the horizontal, vertical and total displacements.
5. Calculate the position of the neutral line. Plot it over the cross-section and explain which part is in tension and which is in compression. Discuss the strains, measured by the lower side strain gage.
6. Plot the measured (average of the 5 sets) and the theoretically predicted strains as a function of the load, both on the same graph and compare the experimental and the theoretical data.
7. Plot the measured (average of the 5 sets) and the theoretically predicted horizontal and vertical displacements as a function of the load and compare the experimental and the theoretical data.
8. Use the measured vertical and horizontal displacements to calculate the total beam deflection. Plot it as a function of the load on the same graph with the theoretically predicted one.

9. Verify by the experimental data that the total displacement is perpendicular to the neutral line.

Geometrical Configuration for Asymmetric Bending

Bending Equations

Bending strain

\[ \varepsilon(y, z) = - \frac{1}{E} \frac{M_z I_{yy} + M_y I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} y + \frac{1}{E} \frac{M_y I_{zz} + M_z I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} z \]

Neutral axis

\[ \tan \alpha = - \frac{M_y I_{zz} + M_z I_{yz}}{M_z I_{yy} + M_y I_{yz}} \]

In our case:

\[ M_z = -P L_g \quad \text{and} \quad M_y = 0 \]

\[ \varepsilon(y, z) = - \frac{1}{E} \frac{M_z I_{yy}}{I_{yy} I_{zz} - I_{yz}^2} y + \frac{1}{E} \frac{M_z I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} z \]

\[ \tan \alpha = - \frac{I_{yz}}{I_{yy}} \]
SHEAR CENTER IN A BEAM OF THIN-WALLED OPEN CROSS SECTION

Objective: To study the shear center theory and to find the shear center experimentally.

Apparatus: A 36”-long aluminum cantilever beam made of C channel (depth 2 in, width 1 in, web and flange thickness 0.13 in, $E=10^7$ psi), 2 digital dial gages, cross-arm, mounted at the tip, Lab View Virtual Instrumentation.

The 2 digital dial gages are located 7” and 5” from the web of the channel on the left and right side of the cross-arm, respectively. The loading system consists of a single 5-pound weight moved to different locations on the cross-arm.

Experimental Steps:

1. Sketch the beam with the cross-arm and location of the digital dial gages. Ten load positions are marked on the cross-arm. Record their locations.
2. Run the “shear center.exe” virtual instrument. Move the load to different locations from left to right along the cross-arm. Save vertical displacements at the ends of the cross-arm (where the displacement gages A and B are located) for each load position (the virtual instrument will prompt you to the next load position in each step).
3. Locate the shear center when moving the load.
4. Load the beam in the shear center in one-pound increments from 1 up to 10 pounds. Record the vertical displacement for each applied load.
5. Repeat steps 2, 3 and 4 five times to obtain a total of five sets of data.

Data evaluation and analysis:

6. Calculate the moment of inertia of the channel.
7. Calculate the position of the shear center and compare with the experimental data (average of the 5 sets).
8. Determine the rotation per applied load using the measured displacements.
9. Plot the two measured vertical displacements and the rotation as a function of the load position all in the same graph. Locate the shear center on the graph and discuss the behavior of the three graphs.
10. Plot the end deflections as a function of the load when the load is in the shear center. Discuss the beam behavior.
11. Calculate and plot the beam end deflection for each load position using the measured vertical displacements. Use equation (2) given below. Discuss the graphs.
1) Position of the shear center, measured from the middle of the web

\[ e = \frac{b^2 (d - t)^2 t}{4I_z} \]

where \( b \) – width, \( d \) – depth, \( t \) – thickness, \( I_z \) – bending moment of inertia of the cross-section

2) Beam deflection

\[ v = \frac{b v_A + a v_B}{a + b} \]

where \( v_A \) and \( v_B \) are the vertical displacements of the points A and B respectively, \( a \) and \( b \) are the corresponding distances to this points from the center of twist and are to be determined from the geometrical configuration given above.
EXPERIMENT #5 (report)

MAXWELL’S RECIPROCITY THEOREM

Object: To verify Maxwell's Reciprocity Theorem.

Apparatus: A steel cantilever beam (see Data Sheet CB2), an SC-2043-SG Eight-Channel Strain Gauge Signal Conditioning Board, VirtualBench Digital MultiMeter, two BC3110 digital dial gages.

Experimental procedure:

1. Set up a four-gage “moment transducer” to measure the moment at the root of the clamped cantilever.
2. Call the point 10” from the clamped end station #1 and the point 20” from the clamped end station #2. Place 5, 10, 15, and 20 lb loads at station #1 and measure the deflections at stations #1 and #2 and record the strain meter reading. Repeat the measurements four times to increase the accuracy by averaging. Note: The load pan and the dial gage cannot both be exactly on the same station simultaneously - make them as close as possible and measure on both sides.
3. Repeat step 2 with the load at station #2.
4. Unload the beam and place the support prop at station #2. Now, the beam is a propped cantilever.
5. Place 20 lb at station #1 and measure the deflection at the point 11” from the clamped end of the beam - call it station #3. Also obtain the strain meter reading. Repeat the deflection and strain measurements four times.

Data Reduction and Analysis:

6. Calculate the theoretical moment transducer constant for the beam.
7. Using the moment transducer constant from step 6 and the average strain meter readings from steps 2, 3, and 5, calculate the experimental moments. Show % errors.
8. Calculate the theoretical deflections at stations #1, #2, #3 that correspond to the measurements in steps 2, 3 and 5. Compare theoretical and experimental values and show % errors.
9. For the clamped cantilever beam, what are the experimental compliance coefficients \( a_{11}, a_{12}, a_{21} \) and \( a_{22} \) from steps 2 and 3. Is Maxwell's Reciprocal Theorem satisfied? Why?

NOTE: Handbook solutions can be used in the calculations.
EXPERIMENT #6 (no report)

DYNAMIC STRAINS

I. IMPACT STRAINS IN A HAMMER HANDLE USING AN OSCILLOSCOPE

Object: To become familiar with the techniques used in measuring and recording impact strains with an oscilloscope

References: VirtualBench Operating Manual

Apparatus: An ordinary hammer having a plastic handle with a foil strain gage, type EA-13-240LZ-120, having resistance and gage factors of 120 $\Omega \pm 0.3\%$ and 2.09 $\pm 0.5\%$, respectively, a 2310 Signal Conditioning Amplifier, VirtualBench Oscilloscope.

Experimental Steps:
1. Connect the $\pm 10V$ output at the rear of the amplifier to Analog Channel #1 (ACH1) of the data acquisition board. Become familiar with the operation of the VirtualBench Oscilloscope.
2. Observe the location of the strain gage on the hammer handle. Include a sketch in the report.
3. Use 1 kHz low-pass filtering, DC coupling, 5V excitation voltage, and 400 gain on the Signal Conditioning Amplifier. Calibrate the oscilloscope to get exactly 1 mV signal for 1 $\mu\text{in}/\text{in}$ strain by adjusting the gain on the amplifier (help: use 2310cali.set for the Virtual Scope).
4. Set the sweep rate to 2 ms/division and switch the Signal Conditioning Amplifier to AC coupling. Practice striking the hammer. When you get an acceptable curve, store it on the screen (help: use hammer.set for the Virtual Scope). Record the measured peak strain and the fundamental vibration frequency. Use cursors C1 and C2 to verify these parameters on one waveform. Also use the cursors to measure the peak-to-peak amplitude ratio $A_2/A_3$ between the second and third cycles.
5. Print out the stored impact strain curve from step 4.
6. Repeat the automated measurement ten times and record the peak strains, the fundamental vibration frequencies, and the $A_2/A_3$ amplitude ratio.

Data Reduction and Analysis:
7. Mount the picture from step 5 and specify the scale on the vertical axis in terms of strain.
8. What is the maximum strain from step 6? How much is the standard deviation and what is the reason for this variation?
9. What is the natural frequency of the hammer handle from step 6? How much is the standard deviation of the frequency and what is the reason for this variation?
10. Calculate the quality factors \( Q \approx \frac{\pi}{\ln(A_2 / A_3)} \) for each repetition of the experiment. What is the average quality factor? How much is the standard deviation of the quality factor and what is the reason for this variation?

II. STRAINS IN A CANTILEVER BEAM USING AN OSCILLOSCOPE

Object: To become familiar with the techniques used in measuring and recording static and dynamic strains with an oscilloscope.

Apparatus: A steel cantilever beam (see Data Sheet CB-2), a 2310 Signal Conditioning Amplifier, VirtualBench Oscilloscope.

Experimental Steps:

1. Start from the same settings on the Signal Conditioning Amplifier as before. Switch back to DC coupling and reduce the cut-off frequency of the low-pass filter to 100 Hz. Calculate how much the gain should be increased to get exactly 10 mV signal for 1 \( \mu \)in/in strain.

2. After the oscilloscope is calibrated, static and dynamic strains can be recorded. First, measure the static strains due to 5, 10, and 15 pounds (help: use beam.set for the Virtual Scope).

3. Next, some pure dynamic strains will be recorded. With no load on the beam (also remove the load tray), displace the tip of the beam until the static strain is 40 \( \mu \)in/in and abruptly release the beam. Record the decaying transient at 500 ms/div rate and print out the result. Increase the sweep rate to 100 ms/div and measure the fundamental frequency of the vibration. Repeat the frequency measurement ten times.

4. Repeat step 3 with loads of 5, 10, and 15 pounds. Note that it will be necessary to balance the bridge for each load before vibrating the beam to eliminate the static component of the strain.

Data Reduction and Analysis:

5. Include the oscilloscope records from steps 3 and 4 in your report with the strain axes properly labeled and the scales given.

6. Make a table of the theoretical static strains, the experimental static strains (from step 2), the maximum dynamic strains (form steps 3 and 4), the theoretical natural frequencies from numerical analysis (see below), the theoretical natural frequencies from the simple lump-element approximation, and the experimental natural frequencies (from steps 3 and 4). The theoretical natural frequencies from numerical analysis are given as 29.5, 10.5, 7.8, and 6.5 Hz, respectively. Calculate % errors between theoretical and experimental static strains and natural frequencies and include them in the table.
Beam: Steel, $E = 30e6$ psi (nominal)

Strain gages:

1, 2, 6, 7, 9 - A5, $R=120\Omega$, $F=1.97$
3, 4 - AX5, $R=120\Omega$, $F=2.03$
5 - EA-13, $R=120\Omega$, $F=2.05$
8 - A5-S6, $R=120\Omega$, $F=1.98$
EXPERIMENT #7  (no report)

UNIAXIAL TENSION TEST

Object: Run a uniaxial tension test to obtain a stress-strain curve and a stress-displacement curve. Material properties are then calculated from these curves.

References: Class notes. MIL-HDBK-5 Govt. pub. on material properties.

Apparatus: Technovate Properties of Material System, Model 9014 arranged for tensile test, manual hydraulic pump, aluminum 6061 alloy tension specimen with 0.125” square test section, Model 3542 axial extensometer, 10,000-lb Omega load-cell, SC-2043-SG Eight-Channel Strain Gauge Signal Conditioning Board, BC3110 digital dial gauge, Fowler digital caliper, newyield.vi and newfailure.vi dedicated Lab View programs.

Experimental Steps:

2. Connect the extensometer to Channel #1 on the Signal Conditional Board. Make sure that the board is set to a full bridge configuration.
3. Run the newyield.vi dedicated Lab View program. Enter the values for the cross sectional area, calibration constant (calculated from the sensitivity of the load cell and the extensometer as provided by the manufacturer).
4. Apply pressure by means of the manual hydraulic pump at the same time carefully following the deformation until the specimen has been strained 0.2%. Release the pressure valve on the pump. Notice that the curve is retracted back to origin (no plastic strain is produced).
5. Apply the pressure again until the strain reaches 0.4% and then release pressure. The curve returns to zero stress with a linear curve parallel to the original linear portion. The strain does not go back to zero (therefore there is a residual plastic strain).
6. Repeat step 5 in strain increments of 0.4% until the strain reaches to 2.0%.
7. Print the recorded stress-strain curve.
8. Disconnect the extensometer and connect the dial gage to the specimen.
9. Run the newfailure.vi dedicated Lab View program.
10. Apply pressure to the specimen slowly until the specimen fails and continuously record the stress-displacement curve. Using the digital caliper measure the dimensions of the cross section at fracture surface.
11. Print the recorded stress-displacement curve.
Data Reduction and Analysis:

12. From these curves, determine the modulus of elasticity, the proportional limit, the 0.2% yield stress, the ultimate “engineering” stress, and the “true” failure stress at the section of fracture. Compare them to the published values for this material.
13. Plot the stress-strain curve and identify the elastic region, the proportional limit, and the plastic region.
14. Examine the specimen after failure. What is the nature of fracture? Can you explain why the pieces have this appearance?
EXPERIMENT #8 (report)

COMBINED STRESS AND STRAIN

Object: To investigate weak secondary bending deformations in the presence of strong primary torsion deformation.

Apparatus: A steel tube with 1.0" O. D. and \( t = 0.063" \) wall thickness, \( E = 26 \times 10^6 \text{ psi} \) and \( \nu = 0.3 \) having type CEA-06-062UR-120 strain gages with a nominal resistance of 120 ohms and a gage factor of 2.05, an SC-2043-SG Eight-Channel Strain Gauge Signal Conditioning Board, VirtualBench Digital MultiMeter.

Experimental Steps:

1. Make a sketch of the experimental set-up showing tube and lever dimensions and the strain gage locations.
2. Arrange the four gages in a strain meter in such a manner as to measure torque and reject bending \( (\varepsilon_m = \varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) \). Show a sketch of the circuit in the report.
3. \( \varepsilon_m = U_m \times M \), where \( M = -4/(U_o GF) \) denotes the multiplication factor used in the Math function to calibrate the VirtualBench Digital MultiMeter. The excitation voltage is \( U_o = 2.5 \text{ V} \), the gage factor is \( F = 2.05 \) for all four gages, and the internal gain of the signal conditioning board is \( G = 10 \), so that \( M = -0.07805 \text{ [V}^{-1}\text{]} \). Instead of reading \( U_m \) directly from the display in \( \mu\text{V} \) and then multiplying it by \( M \) to get the strain in \( \mu\text{in/in} \), use the Math function to calibrate the DMM to \( 1 \mu\text{in/in per 1 } \mu\text{V display sensitivity. Balance the strain meter first by zeroing the Strain Gauge Signal Conditioning Board and then by zeroing the DMM.} 
4. Load the tube by 20 pounds using a torsional lever arm of \( a = 0.5", 1", ... 5" \) (ten steps) from the centerline of the tube. Record the strain meter readings. Unload and check zero.
5. Repeat the measurements in step 4 two more times and average the three sets of data to obtain better accuracy.
6. Arrange the four gages in a strain meter in such a manner as to reject torque and allow the detection of bending deformation \( (\varepsilon_m = \varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4) \). Balance the strain meter first by zeroing the Strain Gauge Signal Conditioning Board and then by zeroing the DMM. Show a sketch of the circuit in the report.
7. Repeat the measurements in step 4 three times and average the three sets of data to obtain better accuracy.
Data Reduction and Analysis:

8. Calculate the ratio of the measured strain in step 4 to the length of the lever arm, \( \varepsilon_m / a \), from theoretical considerations.

9. Plot the average strain meter readings from steps 4 and 5 as a function of the length of the lever arm. Is it linear? Is the slope similar to the one calculated in step 8?

10. Calculate the ratio of the measured strain from step 7 to the theoretical prediction. Assume that the centers of the strain gages are approximately 0.1" from the neutral line.

11. Plot the average strain meter readings from step 7 as a function of the length of the lever arm. Is the strain constant? Is the value similar to the one calculated in step 10 or smaller? Why?

12. Comment on the role of shear deformations in the experiment.
EXPERIMENT # 9

BEAM-COLUMNS (no report)

Objective: To verify the predictions of beam-column theory.

References: Class notes. MIL-HDBK-5 Govt. pub. on material properties.

Apparatus: Technovate Properties of Materials System, Model 9014 arranged for buckling test, manual hydraulic pump, aluminum 6061-T6 alloy buckling specimens with 0.25” OD and 0.18” ID, 10,000-lb Omega Load-Cell, SC-2043-SG Eight-Channel Strain Gauge Signal Conditioning Board, Buckling.vi dedicated LabVIEW Program.

Experimental procedure:

1) Run the Buckling.vi dedicated LabVIEW program. Enter the value for Load-Cell calibration constant, which is calculated from the sensitivity of the load cell as provided by the manufacturer.

2) Using the suitable supports required for the pinned-pinned configuration, mount the 11” specimen in the Model 9014 Technovate Properties of Materials System arranged for buckling test. Use the manual hydraulic pump to proceed with this step but make sure that the specimen is not under any compressive load.

3) Rotate the mounted specimen to check if there is any compressive load on the specimen. The existence of a relatively high frictional force at the fitting points is an indication of a compressive load, which means that you have to relieve the pressure caused from the hydraulic pump by opening the relief valve.

4) Apply successive increments of pressure at a relatively slow constant rate by means of the manual hydraulic pump. For each increment, apply relatively small lateral forces on the beam and check its effect on the display.

5) Continue loading the specimen at the same rate until the load stops behaving in an elastic manner under the applied small lateral pulses. Try to stop before excessive bending (≈1/4”) occurs. Open the hydraulic pump relief valve. The maximum load measured represents the critical buckling load.

6) Print the recorded Load-Load curve and clear the program.

7) Repeat steps 1-6 for the same specimen three times and check the measured critical buckling load.

8) Overload the specimen until it has a noticeable buckling shape (≈1/4-1/2”). Open the relief valve and remount the specimen again.

9) Repeat steps 1-6 for the bent specimen three times and check the resulting critical buckling load.

10) Straighten the buckled specimen as much as possible and repeat steps 1-6 three times. Check the resulting critical buckling load.
11) Change the supports on the Model 9014 Technovate Properties of Materials System for buckling a new specimen under the pinned-fixed configuration.

12) Repeat steps 1-6.

13) Change the supports on the Model 9014 Technovate Properties of Materials System for buckling a new specimen under the fixed-fixed configuration.

14) Repeat steps 1-6.

15) Repeat steps 1-6 and 11-14 for the 5” specimen.

Data reduction and analysis:

16) Compute the theoretical buckling loads for each case tested in the previous steps. The theoretical critical buckling loads are presented in Table (1).

<table>
<thead>
<tr>
<th>Column End Condition</th>
<th>Euler’s Equation for Critical Buckling Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinned-Pinned</td>
<td>$P_{cr} = \frac{\pi^2 EI}{L^2}$</td>
</tr>
<tr>
<td>Pinned-Fixed</td>
<td>$P_{cr} = \frac{\pi^2 EI}{(0.7 \ L)^2}$</td>
</tr>
<tr>
<td>Fixed-Fixed</td>
<td>$P_{cr} = \frac{\pi^2 EI}{(0.5 \ L)^2}$</td>
</tr>
</tbody>
</table>

Table (1): Euler’s Critical Buckling Loads for Different End Conditions

17) Compare the theoretical and experimental buckling values. Explain the reason for these differences.

18) For the 11” specimen under the pinned-pinned end conditions. Tabulate the theoretical and experimental critical buckling load resulting from steps 7 and 10. Explain the variation in these results.

19) For the 11” specimen under the pinned-pinned boundary conditions. Compare the measured critical buckling load resulting from step 9 with those obtained from step 18. Discuss your results.

20) Do you think that some of these columns can be considered “short” for this study? Discuss this.

21) For the 5” specimen, draw the final column shapes. How can you explain the different shapes according to the column end conditions?