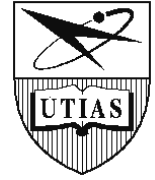




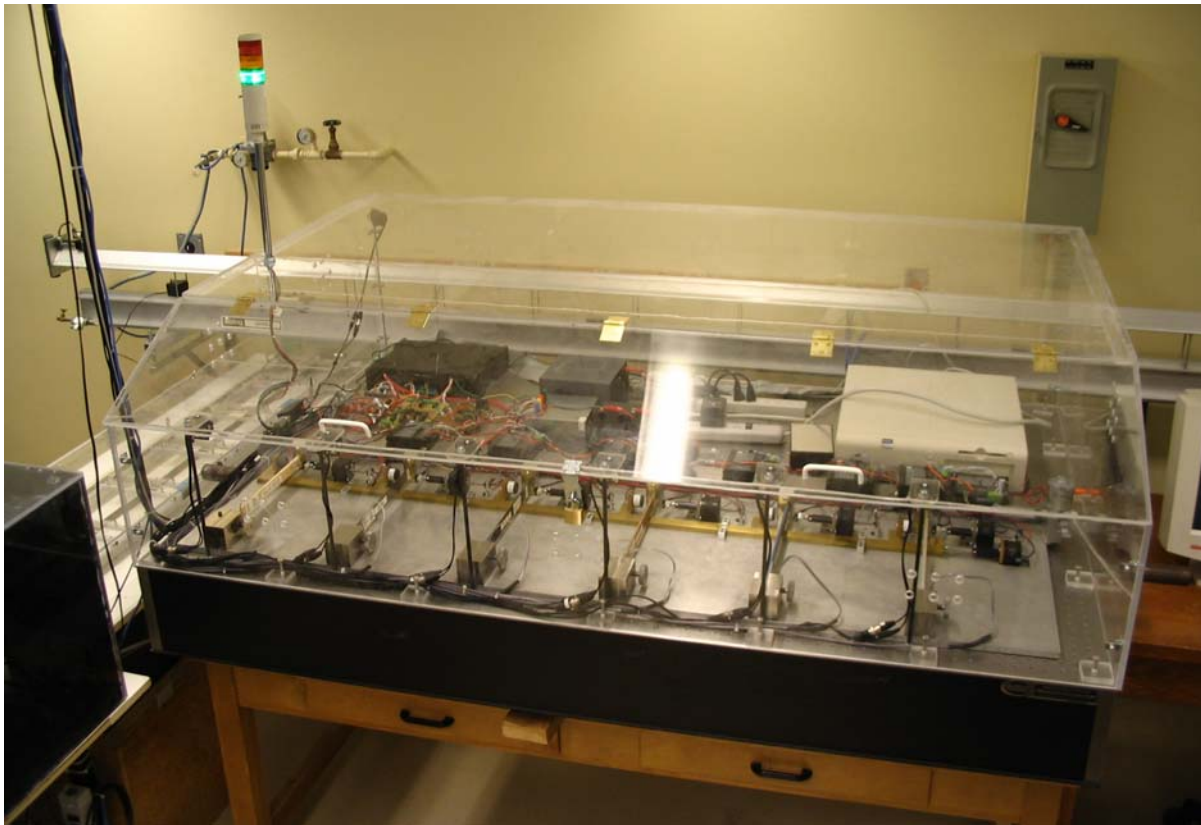
AER 303F Aerospace Laboratory I



Strain Gage and Materials Testing

<http://sps.aerospace.utoronto.ca/labs/raal>

Experiment Duration: **150 min**



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1. Purpose

Some applications of foil strain gages are demonstrated using pre-gauged cantilever beams. The Elastic Modulus, Poisson's ratio and material loss factors for a variety of materials including some advanced composites are obtained by analysis from the measured strains from lateral and axial strain gages. Some observations are also made for the effect of temperature on strain gage response. A computer-aided data acquisition system is used to collect and record strain data from the strain gages.

2. Apparatus

- Stress-strain test bed with pre-gauged cantilever beams.
- Cantilever beams: balsa wood, steel, graphite reinforced epoxy (GRE), Kevlar reinforced epoxy (KRE), damped steel, and plexiglass with lateral and axial strain gages.
- 120Ω foil strain gages (CEA-13- 125UW-120), Gage factor = 2.11
- Honeywell FSG15N1A force sensors.
- AEC Magnetics electro-magnets for exciting the beams.
- Haydon linear actuators for applying force to the beams.
- Data acquisition system (DaqBoard2000™ PCI Board & DBK16™ Module).
- Power supplies and power control unit.
- Web cams and audio system.

3. Notation and Numerical Constants

A	area (m ²)	P	power(W) <u>or</u> load(N)
C	damping coefficient (Ns/m)	ρ	resistivity (Ωm) <u>or</u> density (kg/m ³)
δ	logarithmic decrement	Q	sharpness of resonance
E	Elastic Modulus (Pa)	R	resistance (Ω)
ϵ	strain (μϵ)	σ	stress (Pa)
ζ	damping ratio	τ_{3dB}	3 dB decay time
η	material loss factor	τ_d	damped oscillation period (s)
f	frequency (Hz)	T	temperature (K)
F	force (N)	t	beam thickness(m)
G	gage factor	V	voltage (V)
I	area moment of inertia (m ⁴)	x	fractional beam length (m)
k_B	Boltzmann constant (1.38 × 10 ⁻²³ J/K)	y	beam width(m)
κ	curvature (1/m)	ω	pulsation (rad/s)
L, l	length (m)	z	beam deflection
M	applied moment (Nm)	Z	beam deflection (oscillation)
ν	Poisson's Ratio		

4. Experiment Setup

The major elements which make up the aerospace undergraduate laboratory stress-strain test bed are indicated in Fig. 1. The test bed operates in parallel, with each beam having a dedicated set of hardware components (e.g., actuators, gages, etc.).

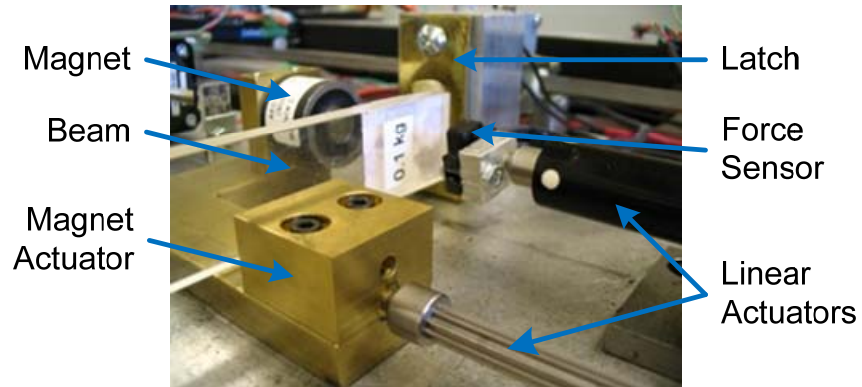


Figure 1: Diagram of the stress-strain test bed

4.1 Cantilever Beams

The cantilever beams, as depicted in Fig. 2, are fixed at one end and free to vibrate at the other. Static loads are applied using a motor-driven force sensor. Free dynamic oscillation can be generated by releasing the beam from a bent position using a door latch. Forced dynamic oscillations can be generated using an electromagnetic excitation actuator to drive the beam. Specifications for each beam are presented in Table 1.

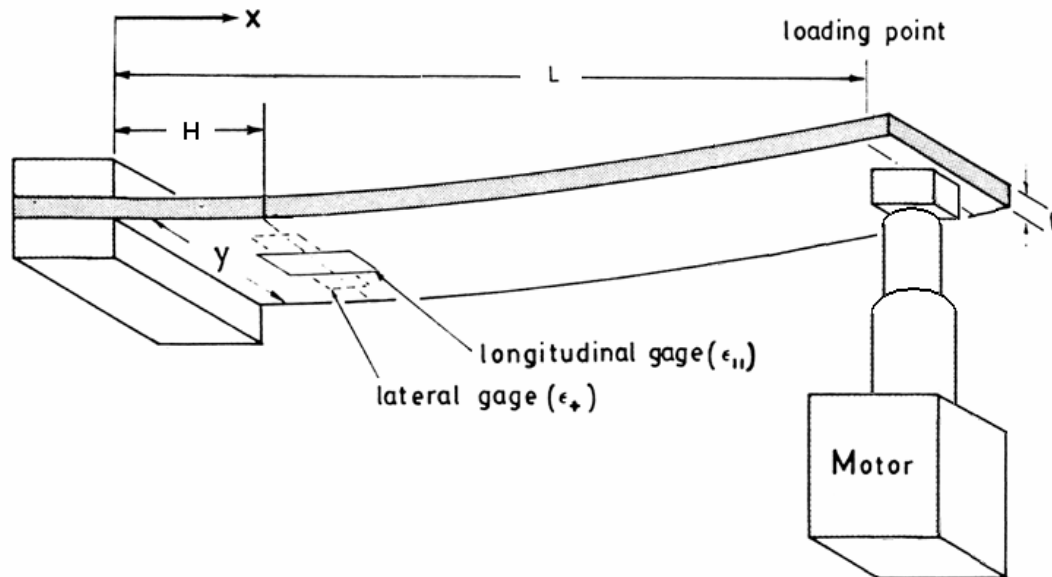


Figure 2: Cantilever beam with strain gages and load applicator

Table 1: Cantilever beam specifications

Beam	Length (m)	L (m)	H (m)	y (m)	t (m)	ρ (kg/m ³)	n_{3dB} (oscillations)
Balsa wood	0.3183(3)	0.282(1)	0.026(1)	0.0254(5)	0.00617(8)	205.9	2
Carbon steel	0.3195(3)	0.278(1)	0.026(1)	0.0253(3)	0.00310(1)	7806	15
Graphite (GRE)	0.3170(3)	0.278(1)	0.026(1)	0.0254(3)	0.00295(5)	1506	11
Kevlar (KRE)	0.3183(3)	0.278(1)	0.025(1)	0.0266(1)	0.00516(1)	1364	5.5
Damped steel	0.3180(3)	0.281(1)	0.026(1)	0.0252(3)	0.00617(3)	1183	1.2
Plexiglass	0.3183(3)	0.282(1)	0.026(1)	0.0254(5)	0.00617(8)	205.9	2

4.2 Data Acquisition System

The data acquisition system consists of a Pentium[®] III workstation equipped with a DaqBoard2000[™] data acquisition (DAQ) board and DBK16[™] strain gage module from IOtech. The DAQ board has 40 digital I/O channels, and a 16 channel analog-to-digital (A/D) converter with 16-bit resolution (i.e. 2^{16} discrete voltage values over the measurement range of 0 to 10V), which is equivalent to a voltage resolution of 0.15 mV. The DAQ board allows the computer software to control electromechanical actuators and collect data from a variety of analog and digital sensors.

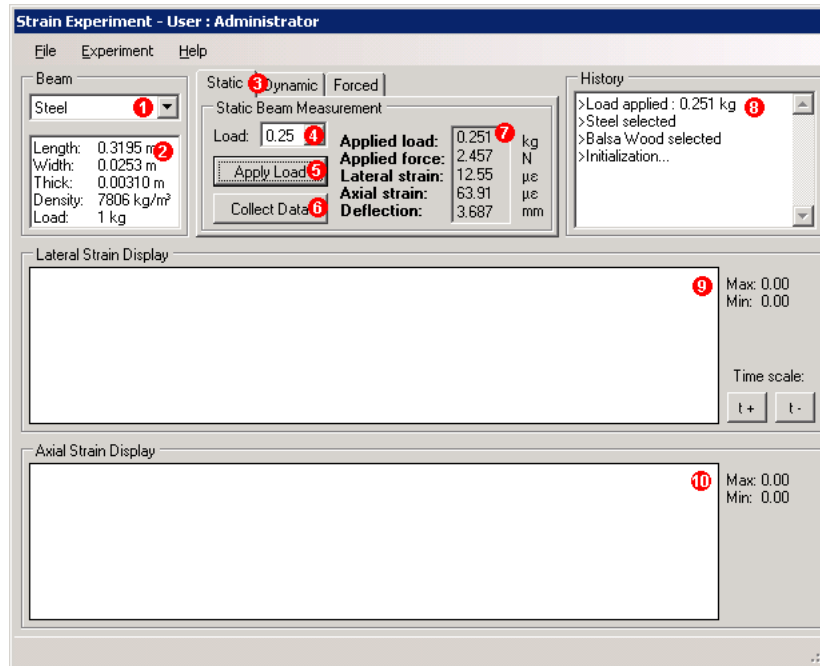
The strain from the lateral and axial gages is measured using foil strain gages that convert strain values to a voltage that can be read by the DAQ board. The output from each strain gage is amplified by the DBK16[™] module, with a variable gain from X100 to X1250.

4.3 Load Applicators

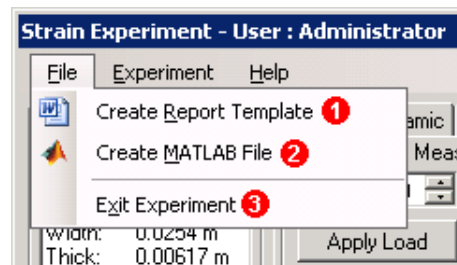
Load is applied to the cantilever beams using a computer-controlled linear force applicator that can apply a load of up to 23 kgf to the beams. The linear force applicators consist of a micro switch force sensor coupled to a linear stepper-motor actuator with a resolution of 0.047625 μm per step. Limit switches are used for homing the stepper motors.

The computer software can control each component of the experiment individually, such as in the case of applying a desired static load to a beam or it can control multiple components simultaneously allowing complex dynamic experiments to be performed. The computer control system enables the experimenter to not only collect data more accurately, but also perform multiple tasks simultaneously.

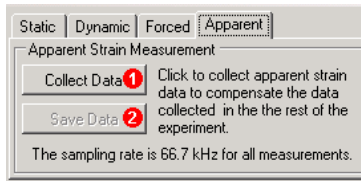
5. Experiment User Interface



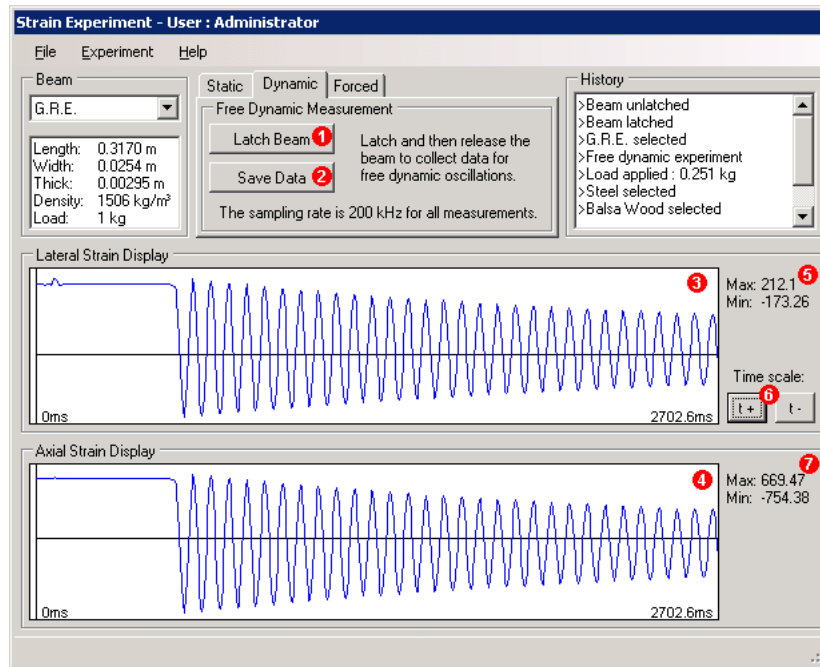
1. Change the currently selected cantilever beam.
2. Displays the specifications for the current beam *estimate*.
3. Select between the *Static*, *Free Dynamic*, and *Forced Dynamic* experiments.
4. Select the load in kg to apply to the beam.
5. Apply the specified load to the current beam.
6. Collect and save force and strain data for the current beam and load.
7. The currently applied load and strain measurements.
8. History of previously executed commands.
9. Lateral strain data is displayed here for the dynamic experiments.
10. Axial strain data is displayed here for the dynamic experiments.



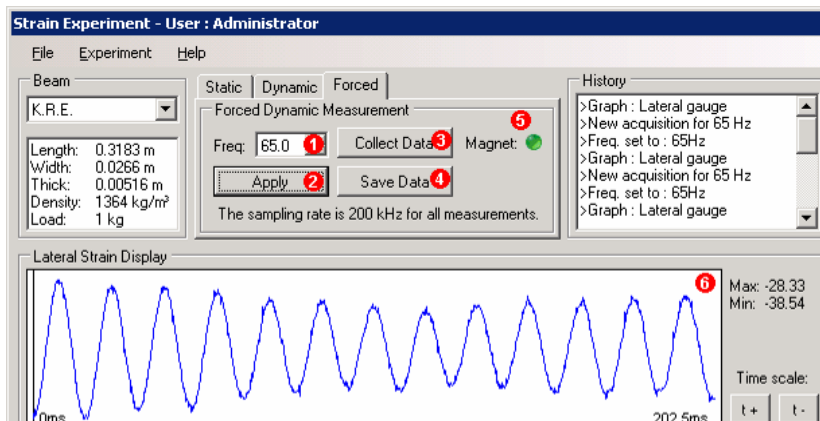
1. Create a report template (.doc) for the experiment and save it to the Portal.
2. Create a MATLAB® file (.m) for the experiment and save it to the Portal.
3. Exit the experiment. Remember to first create a report template and MATLAB® file.



1. Collect apparent strain data for the current beam. (~2:30 minutes).
2. Save the current apparent strain data for the selected beam.



3. Latch and unlatch the currently selected beam (automatically records strain during unlatch).
4. Save the current strain data for the selected beam.
5. Displays the lateral strain for the current beam *after* unlatching it.
6. Displays the axial strain for the current beam *after* unlatching it.
7. Max and min lateral strain for the current experiment.
8. Zoom the time scale in and out.
9. Max and min axial strain for the current experiment.



1. Select the excitation frequency for the magnet.
2. Apply the specified excitation frequency to the magnet.
3. Collect live strain data for the oscillating beam.
4. Save the current strain data for the selected beam.
5. Indicates the state of the magnet (green = magnet powered).
6. Displays the strain for the current beam.

6. Structural Materials

The operational requirements of aerospace vehicles and structures have increased the need for materials with high strength, low density, good thermal stability, high damping and low fatigue characteristics. Graphite and Kevlar reinforced epoxies satisfy many of these needs since they may be 'tailored' to fit specific requirements by manipulation of the fiber orientation during lamination. These materials also produce low radar signatures and are used in the manufacture of 'stealth' aircraft.

The spin-off from research in this area has resulted in composite bicycle frames, tennis racquets and golf clubs. The advanced composite material field, which is at the leading edge of materials technology, is fascinating and extensive, and some preliminaries are covered in Refs. 1 and 2. Currently, however, traditional metals, alloys, and plastics are the major source for aerospace materials and even wood has a niche in some airborne applications.

The density or specific gravity of a material is of obvious importance since this is a factor in determining the stiffness-to-weight ratio or Specific Modulus (E/ρ). After concluding this experiment you may appreciate why the largest wingspan aircraft ever built (the 'Spruce Goose') was constructed mainly from wood.

The thermal and electrical conductivity, lubricity, wearing properties, hardness, X-ray absorption, damping and more topically atomic oxygen resistance are just a few of the parameters that are involved in selecting a material for a particular application. However, strength and stiffness are still the dominating primary factors that initially govern material selection.

Atomic oxygen resistance is presently of major interest because the atmospheric concentration for this gas exceeds all other species except helium above an altitude of 160 km. This gas is highly reactive and has been implicated in the degradation of advanced composite materials exposed to a space environment.

6.1 Strain Gages

Strain gages are used in some accelerometers for the determination of the position and speed of missiles and aircraft, they are employed in dynamometers for automobile testing and may be used to measure gun recoil forces. The digital bathroom scale often derives its output from a strain gage and this same principle is used to weigh a 100,000 kg. aircraft to ± 150 kg and determine its center of gravity to within a few centimeters.

Despite such esoteric applications the fundamental operating principle of a strain gage is very simple; relying on the fact that the change in the cross-sectional area of a wire, when stretched or compressed, produces a concomitant change in the wire resistance.

Starting from the resistance relation for a conductor:

$$R = \frac{\rho L}{A} \quad (1)$$

where ρ is the resistivity. It can be shown that if ν is Poisson's ratio then:

$$\left(\frac{dR}{R}\right) = 1 + 2\nu + \left(\frac{d\rho}{\rho}\right) \left(\frac{dL}{L}\right) \quad (2)$$

The right-hand side of this equation is called the "Gage Factor" (G) and thus we may write the "Strain Gage equation" as:

$$\frac{\Delta R}{R} = G\varepsilon \quad (3)$$

where ε is the strain.

6.1.1 Foil Gages

Modern foil gages are formed by photo etching techniques which leave a thin (~ 0.0002 ") metal layer attached to an insulating backing (~ 0.002 "). The conducting foil material comes from the group of metals that have low thermal expansion coefficients which includes Nichrome, Constantan and platinum tungsten alloys. The gages are shaped to give a preferential axis for strain measurement as depicted in Fig. 3.



Figure 3: Foil strain gage configuration

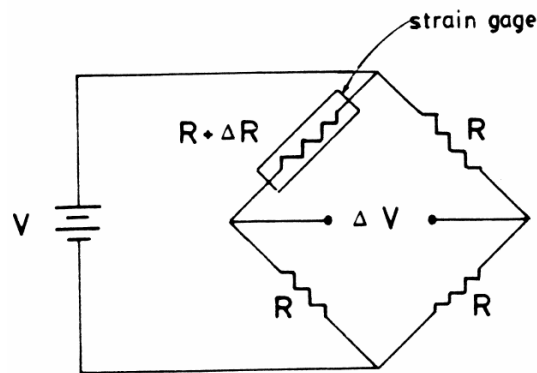
Custom gages fulfill many special needs but in regions where the strain gradient is very high even a gage with the smallest dimensions may be inadequate to provide the spatial resolution required for a correct interpretation of a strain field. For these cases an average gage reading over a small defined area is used in conjunction with a Photoelastic survey, a brittle lacquer test, or a holographic study.

The range of operating characteristics for foil gages is typically:

Operating temperature:	-270 to +370C
Strain limits:	± 5% (50000 $\mu\epsilon$)
Fatigue life:	± 2200 $\mu\epsilon$ for 10^7 cycles
Active gage area:	0.4 mm × 0.4 mm to 150 m × 8 mm
Gage factor:	2 to 4.5 (as specified)
Nonlinearity ($\Delta R/\epsilon$):	0.02%
Max DC gage current :	~50 mA
Resistance:	120, 350, 700, 5000, 10000 ohms ± 0.2%
Dynamic response:	~40 KHz for a 6 mm gage

6.1.2 Usage of Strain Gages

In Fig. 4 a bridge circuit is used to measure the voltage V , which by Equation (3) is proportional to the applied strain. In this experiment single active gages are used in the bridge circuit shown. For some applications 2 or 4 active gages are used in a bridge; this can both increase the available output and also provide temperature compensation.



$V=2$ volts for this experiment

Figure 4: Strain gage bridge circuit

$$\Delta V = \frac{V\Delta R}{4R} = \frac{VG\epsilon}{4} \quad (4)$$

The power consumed by each gage is given by:

$$P = \frac{V^2}{4R} \quad (5)$$

This power is dissipated predominantly by heat transfer to the member on which the gage is mounted, and can cause problems where the latter is a poor thermal conductor. Inadequate thermal transfer results in expansion of the gage elements producing an 'apparent strain' which is usually manifested as a drift in the bridge output under steady load conditions.

If the gage temperature is known, then appropriate corrections can be applied to compensate for the apparent strain, but the problem is best addressed by careful selection of the gage operating parameters.

From the expression just given it can be seen that gage heating is more effectively controlled by lowering the bridge potential than increasing the gage resistance. Although a larger gage resistance does increase the output signal it also increases the magnitude of 'pick up' from electronic sources. For large values of R , Johnson noise, which has its origin in thermal electronic motion, may be of consequence, especially when small strains are being monitored.

The Johnson noise potential V_n is given by:

$$V_n = \sqrt{4k_B T \Delta f R} \quad (6)$$

The Johnson noise potential may be significant due to the increase in temperature resulting from self-heating when gages are mounted on insulators. For dynamic measurements the frequency bandwidth seldom exceeds 20 KHz but this alone increases V_n by more than 2 orders of magnitude, when compared to the equivalent DC measurement.

6.1.3 Transverse Sensitivity

A strain gage will also possess some strain sensitivity in the direction perpendicular to its principal axis. In a uniaxial strain field, this transverse sensitivity is of no concern because the gage factor has been determined under such conditions. However, in a biaxial field corrections for the transverse sensitivity must be applied for accurate results, as is the case here for the determination of Poisson's ratio.

Thickening of the loop ends and other design factors reduce the transverse sensitivity contribution to 2% for the gages as used in this experiment. Although this factor is small, the lateral gage in Fig. 2 is subjected to relatively large strains perpendicular to the principal axis and the transverse sensitivity must be compensated if an accurate evaluation of Poisson's ratio is required.

6.1.4 Semiconductor Gages

The piezoelectric effect is used in some commercial strain gages. These are constructed of P- or N-doped silicon and may have gage factors up to 200, an obvious advantage where increased sensitivity is required.

Greater care must be exercised when using semiconductor gages because their gage factor varies markedly with both temperature and the strain level. They find their greatest use in high output

transducers such as load and pressure cells where circuit compensation can minimize the adverse effects mentioned.

6.1.5 Bonding Foil Gages

For reliable strain measurement it is essential that any movement of the member to which the gage is attached be transmitted faithfully to the gage. Cyanoacrylates or epoxies are currently the adhesives of choice and with care excellent installations can be affected quite quickly. Detailed instructions for such procedures and more detailed information on gages and bridge configurations are available in the laboratory.

6.2 Material Properties

Fig. 5 shows some features which are common to many structural materials; the curve is generally applicable although deviations do occur. For example, hard and brittle materials such as cast iron have no yield point, and other factors such as creep and hysteresis may make it difficult to define a single curve for a particular material.

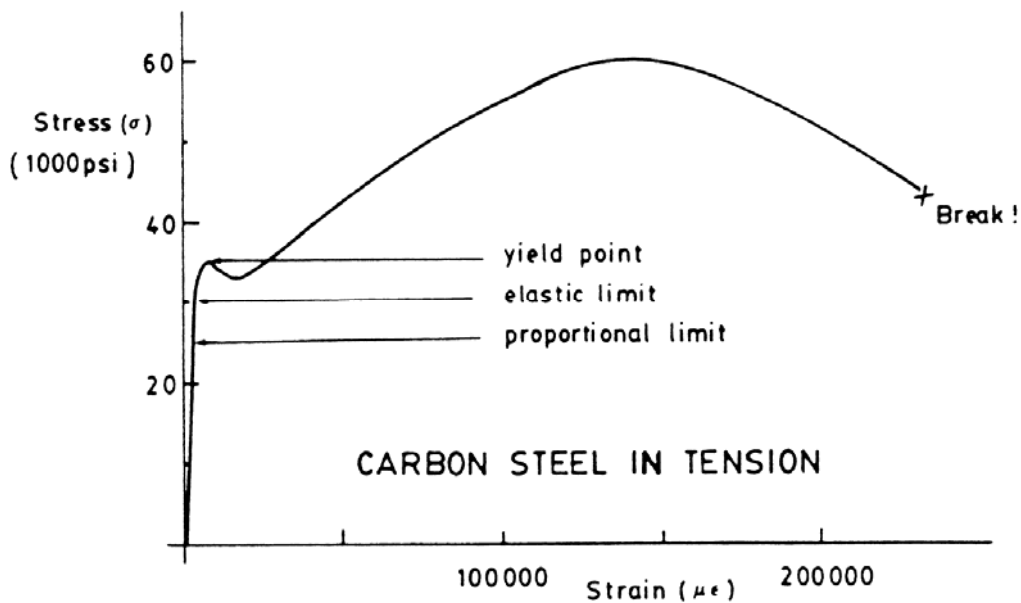


Figure 5: Stress-strain curve for carbon steel

This experiment is confined to the regime below the proportional limit (0.2% yield) in Fig. 5 since the Modulus of Elasticity or Young's Modulus (E), and Poisson's Ratio (ν), as described below, are only defined in this region.

$$E = \frac{\sigma}{\epsilon_{\parallel}} \quad (7)$$

$$\nu = -\frac{\epsilon_{\perp}}{\epsilon_{\parallel}} \quad (8)$$

In these expressions ε_+ and $\varepsilon_{||}$ refer to the lateral and axial strains respectively and ν is < 0.5 for all materials.

Strain ε is the change in length per unit length under an applied stress σ :

$$\varepsilon = \frac{\Delta L}{L} \quad (9)$$

Stress σ (a derived quantity) cannot be measured directly but the surface stress along a cantilever beam can be determined from the following equation if the load P is known.

$$\sigma = \frac{6P(L-x)}{yt^2} \quad (10)$$

6.2.1 Determination of E and ν

Fig. 2 shows a cantilever beam which may be stressed in discrete steps by mass loading, or continuously using a screw micrometer. Equation (7) demonstrates that E is the slope if you plot stress σ vs. axial strain $\varepsilon_{||}$. Stress σ is calculated with equation (10) at the point $x = H$.

Poisson's ratio, corrected for the transverse sensitivity of the gage is, for this experiment, given by:

$$\nu = -0.98 \frac{\varepsilon_+}{\varepsilon_{||}} \quad (16)$$

So, Poisson's Ratio can be found with the slope on $\varepsilon_{||}$ vs. ε_+ plot.

6.2.2 Damped Free Vibration

Large space structures such as antenna arrays or solar panels must be very stiff and highly damped. Unfortunately, for most space qualified materials, these are conflicting requirements. Composites, because of their high specific modulus and good damping properties, have distinct advantages in these areas, but passive and active damping techniques are both currently under investigation.

For convenience some useful formulas are given here; more information is available from many texts which cover this area well. Briefly, if a linear, second-order system with one degree of freedom is excited, its equation of motion in general form is:

$$m\ddot{x} + F_d + kx = F(t) \quad (17)$$

where $F(t)$ is the excitation force and $F_d = c\dot{x}$ is the damping force. For free damped vibration:

$$m\ddot{x} + c\dot{x} + kx = 0 \quad (18)$$

(Note: In this section x represents the beam displacement.)

For the experiment we will consider only the under-damped oscillatory case for the initial conditions $x(0), \dot{x}(0)$:

$$x = e^{-\zeta\omega_n t} \left[\frac{\dot{x}(0)\zeta\omega_n x(0)}{\omega_n \sqrt{1-\zeta^2}} \sin \sqrt{1-\zeta^2} \omega_n t + x(0) \cos \sqrt{1-\zeta^2} \omega_n t \right] \quad (19)$$

where the damped oscillation frequency is:

$$\omega_d = \frac{2\pi}{\tau_d} = \omega_n \sqrt{1-\zeta^2} \quad (20)$$

The dimensionless quantity ζ is a ratio of the damping value in question to the critical damping coefficient C_c .

$$\zeta = \frac{C}{C_c} \quad (21)$$

6.2.3 The Logarithmic Decrement δ

The following expressions apply to the damped oscillation, shown in Fig. 6:

$$\delta = \frac{1}{n} \ln \frac{x_0}{x_n} = \zeta \omega_n \tau_d = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \quad (22)$$

For the materials examined here $\zeta \ll 1$, therefore:

$$\delta = 2\pi\zeta \quad (23)$$

Observation of the oscillatory decay may begin at any convenient amplitude - for the vibrating beam one would select a time where good periodic motion is achieved. If the amplitude at this time is x then it is customary to use the 3 dB, or half power points to mark the termination of the observation interval.

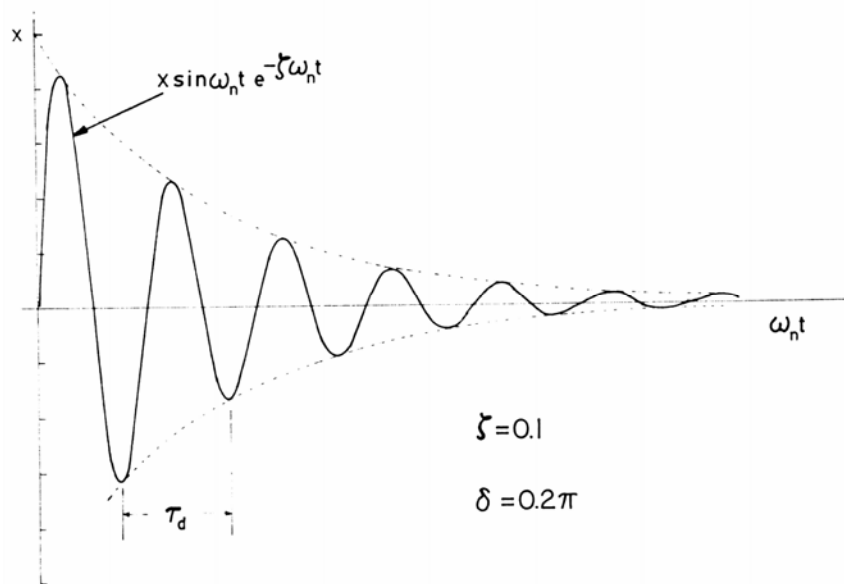


Figure 6: Damped oscillation

6.2.4 Resonant Vibration of a Cantilever Beam

A magnetically driven beam may be forced to vibrate at any frequency but will do so most efficiently in its fundamental mode, with a single node at the clamp. For this case the resonant frequency f_r in SI units is:

$$f_r = \frac{0.16157t}{L^2} \sqrt{\frac{E}{\rho}} \quad (24)$$

Typical behavior in the beam amplitude (Z) with driving frequency is illustrated in Fig. 7.

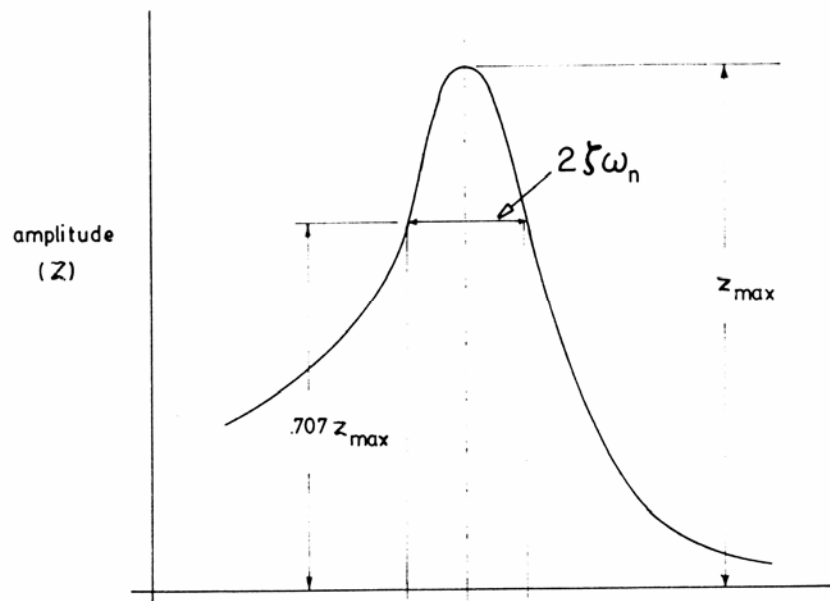


Figure 7: Vibrating beam resonance profile

Q is defined as the peak energy divided by the energy loss per cycle, or with some alternates:

$$Q = \frac{U}{\Delta U} = \frac{\omega_n}{\omega_2 - \omega_1} = \frac{f_n}{\Delta f} = \frac{1}{2\zeta} \quad (25)$$

6.2.4 Material Damping

For the purpose of this experiment the primary goal is the inter-comparison of damping characteristics of a variety of materials. It will be adequate to express your results in terms of the 'material loss factor' (η).

$$\eta = \frac{\delta}{\pi} \quad (26)$$

The extent of η for some common materials is indicated in Fig. 8 below.

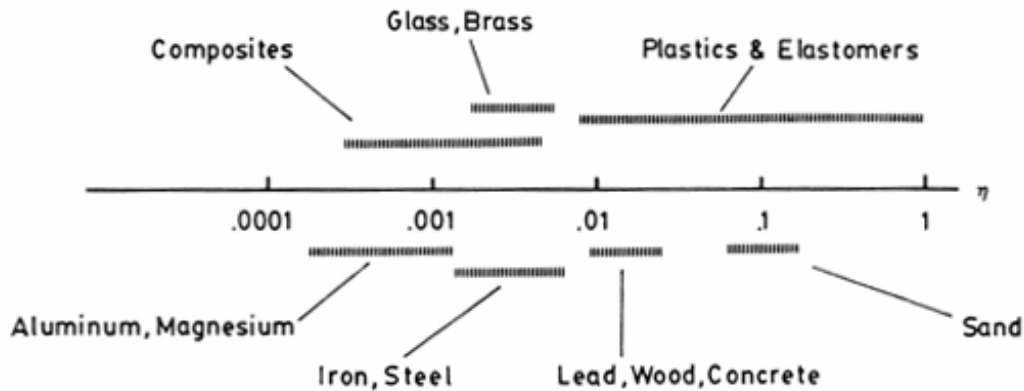


Figure 8: Material loss factor for common materials

7. Experiment Design

Some preparation and research will be required to understand your experiments prior to actually performing the tests in this experiment. Each test should not be viewed as an independent activity. The results of one test *may* prove useful in defining the parameters of another test.

Two MATLAB® files, named as “strain.m” and “aer.m,” can be generated by the interface to compute the resonance frequency and decay constant from the results of the Free Dynamic Experiment using System Identification techniques. (aer.m is part of the MATLAB® System Identification toolbox.) In order to run the function, use the following command in MATLAB® workspace:

```
>> strain ('.\<name of the folder where the data are saved>\<filename>.txt')
```

Note that the working directory must be the Strain folder. If you type in “help strain” in MATLAB® workspace you will find a brief description of the function. You need, however, to open the “strain.m” file and study the program and modify it for further analysis.

The experiments to be performed are:

Apparent Strain Measurement: To record the apparent strains in the gages under zero applied stress use the controls under the “*Apparent*” tab. Click the “*Collect Data*” button to collect data from the strain gages. Click the “*Save Data*” button after a test to save the collected data in a text file. Please be patient, data will be collected for approximately 2.5 minutes during this measurement. **Note:** You will need to play with the setup a bit before taking this measurement to allow the system to stabilize.

Static Beam Measurement: To record the strains in a beam during a static stress state use the controls under the “*Static*” tab. Select the load to apply using the number box and then click the “*Apply Load*” button. Click the “*Collect Data*” button to collect data and save data from the strain gages and force sensor. Collect more than one measurement for each applied load.

Free Dynamic Strain Measurement: To record the strains in a beam during a free oscillation use the controls under the “*Dynamic*” tab. Click the “*Latch Beam*” button to bend the beam and restrain it with the mechanical latch. Click the “*Unlatch Beam*” button to release the beam and collect strain data (records for ~13 seconds). Click the “*Save Data*” button after each test to save the collected data in a text file (this can take several minutes due to the large size of the data sets).

Forced Dynamic Strain Measurement: To record the strains in a beam during a forced oscillation, use the controls under the “*Forced*” tab. Select the excitation frequency using the number box and then click the “*Apply*” button. Click the “*Collect Data*” button to collect data from the strain gages during the oscillation. Click the “*Save Data*” button after each test to save the collected data in a text file (wait till any transients die down before saving data).

7.1 Apparent Strain

Perform the **Apparent Strain Measurement** for each of the beams. The resultant data represent the apparent strain under zero stress, which is a function of thermal drift, gage bonding interactions, and other aging effects. Balsa Wood is a good thermal insulator and hence the strain gages will undergo significant self heating during the course of an experiment. This effect will manifest itself as a large apparent strain.

To analyze the resultant data first use a smoothing function (e.g., `smooth()` or `spline()` in MATLAB®) to eliminate any noise in the data. The resultant curves (plotted versus time) represent the apparent strain of the gages, which can be used to compensate the rest of the strain measurements in the experiment.

7.2 Static Beam Experiment

Perform the **Static Beam Measurement** for each of the beams at a variety of loadings. Choose sufficient number of loadings to cover the entire range (0 to maximum load for each beam) properly. For each loading take multiple measurements to determine the effects of noise, transients, and other phenomena on the data.

Switch to the Static Beam Experiment by either clicking the “*Static*” tab or selecting “*Static Beam*” from the “*Experiment*” menu. To change the applied load on a beam enter the desired load in the number box (in kgf) and click “*Apply Load*”. It can take several seconds for the linear force applicators to zero-in on the exact force value. The display will be updated with fresh data once the load has been accurately applied. Click the “*Collect Data*” button to take a new set of readings; clicking this button will also automatically save the data. The maximum loading for each beam is displayed in the beam property display.

7.3 Free Dynamic Oscillations

Perform the **Free Dynamic Strain Measurement** for each of the beams. One dataset should be sufficient for each beam, although you may want to perform multiple measurements for a single beam to quantify any drift in the sensors.

Switch to the Free Dynamic Beam Experiment by either clicking the “*Dynamic*” tab or selecting “*Free Dynamic*” from the “*Experiment*” menu. Please be patient after clicking the “*Save Data*” button, it can take up to several minutes for the application to write the 300,000 data points for each strain gage to a text file. Due to the large size of the data files (~6MB each) each dataset is saved in two formats: a full version for analysis in MATLAB® (located in \Strain*<name of the folder where the data are saved>*\Matlab\), and a truncated version for plotting in Excel® (located in \Strain*<name of the folder where the data are saved>*\Excel\). **Note:** Damped Steel beam does not have a lateral strain gage.

7.4 Forced Dynamic Oscillations

Perform the **Forced Dynamic Strain Measurement** for each of the beams. One dataset collected at the resonant frequency should be sufficient for each beam, although you may want to perform multiple measurements for a single beam to quantify any transients while changing frequency.

Switch to the Forced Dynamic Experiment by either clicking the “*Forced*” tab or selecting “*Forced Dynamic*” from the “*Experiment*” menu. To change the magnet excitation frequency applied to each beam, enter the desired frequency in the number box (in Hz) and click “*Apply*”. Click the “*Collect Data*” button to take a new set of readings. A piece of thin steel sheet attached to the beam tip is magnetically attracted by a magnet solenoid coil driven at a frequency (f_r) to match the beam's natural resonance. Determine the resonant frequency by finding the excitation frequency that yields the greatest oscillation amplitude. Use the webcams and strain displays to judge the oscillation amplitude. When looking at the graphs, pay attention to the scales.

8. Discussion of Results

8.1 Apparent Strain

1. Why does the steel beam show no significant drift in the strain data?
2. Plot each of your smoothed datasets on the same graph and comment on any significant differences between the curves.
3. Suggest a method to compensate for the thermal drift component of the apparent strain effect in real-time.
4. In what other measurements in the entire experiment does apparent strain manifest itself? Support your answer with some data (a simple plot is sufficient).
5. Can you determine the change in Gage factor with time from the apparent strain data? How does this compare to the specifications stated in the datasheet?

8.2 Static Beam Experiment

1. Use Equation (10) to calculate the stress on the beams for the applied loads and tabulate the results for all beams.
2. Plot stress vs. axial strain for each beam and use the result to calculate Young's modulus.
3. Plot axial vs. lateral strain for each beam and use the result to calculate Poisson's ratio.
4. How do the static material properties compare between the steel and damped steel beams? Explain any significant differences.
5. How do your results compare to those reported in the literature. Be specific about any and all discrepancies, and provide an explanation for each.
6. Plot load vs. deflection for each beam. Does the result agree with theory? Explain any discrepancies. Include in your answer the theoretical formulation that you used from literature.

8.3 Free Dynamic Oscillations

1. Show that for a cantilever beam, the surface strain is only a function of the beam dimensions and the end deflection.
2. Use MATLAB[®] to determine the decay constant and fundamental frequency for each beam. Tabulate the results. (The "strain.m" function provides both System Identification and Fourier Transform approaches for these computations. Note that, however, System Identification approach may not yield reliable results for some of the beams.)
3. For one of the beams determine the decay constant and fundamental frequency using the following three techniques and compare and discuss the results:
 - 1) System Identification (from the MATLAB[®] file).
 - 2) Fourier Transform: Plot the strain signals in frequency space and identify the fundamental resonance peak.
 - 3) Curve Fitting: Use MATLAB[®] to curve fit a portion of the data to the equation in Fig. 6. You must enter reasonable initial values and bounds for the fit to converge.
4. Which material decays the fastest and why?
5. Perform a *rough* calculation to indicate the contribution of air-damping to the beams' performance.

6. The polymer material in the Damped Steel beam removes energy from the beam's vibration: By what factor is the rate of energy removal increased? Comment on where and why this material might be used.
7. Perform a complete error analysis for the Steel beam. Which hardware component introduced the greatest uncertainty in the data?
8. Estimate ζ for a familiar object or process (e.g., basket ball, car suspension, etc.). Briefly describe your method and estimate the error in your computation. Identify (and quantify if practical) any factors that might directly influence the ζ of your system.
9. For one of the beams calculate the decay constant and resonant frequency using both the full dataset and truncated dataset. Is there any significant difference in the results? Is there any significant difference in the error? What does this say about the sampling rate used for collecting strain measurements?


8.4 Forced Dynamic Oscillations

1. Calculate ΔR for $5 \mu\epsilon$ (microstrain) for the given experimental setup. Include all sources of error in your calculations.
2. Compare the measured values for the fundamental resonance of each beam with those you computed from the decay analysis in the **Free Dynamic Oscillations** Experiment.
3. Is there a significant difference in the fundamental resonance for the steel and damped steel beams? Why?
4. Calculate Young's modulus for each beam using Equation (24). How do the results compare to those from the **Static Beam** Experiment? Why?

9. References

- [1] Broutman, L. J., and Krock, R. H., *Modern Composite Materials*, Addison Wesley, 1967.
- [2] Holister, G. S., and Thomas, C., *Fibre Reinforced Materials*, Elsevier Publishing Co., 1967.
- [3] Read, B. E., and Dean, G. D., *The Determination of Dynamic Properties of Polymers and Composites*, 1978.

Appendix A: Strain Gage Specifications

 <p>Micro-Measurements Division</p> <p>MEASUREMENTS GROUP, INC. RALEIGH, NORTH CAROLINA</p> <div style="border: 2px solid black; padding: 5px; text-align: center; font-weight: bold; font-size: 1.2em;"> PRECISION STRAIN GAGES </div>	OPTION CODE 952512	LOT NUMBER R-A41AF32	QUANTITY 5 GAGES	K_t +1.3%	GAGE FACTOR AT 75° F 2.11 ± 0.5%	RESISTANCE IN OHMS 120.0 ± 0.3%	GAGE TYPE CEA-13-125UM-120	CEA-13-125UM-120
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GENERAL INFORMATION: SERIES CEA FEATURE GAGES

GENERAL DESCRIPTION: CEA Gages are a general purpose family of constantan strain gages widely used in experimental stress analysis. The gages are supplied with a fully encapsulated grid and exposed copper-coated integral solder tabs to which heavy lead wires may be soldered directly.

TEMPERATURE RANGE: -100° F (-75° C) to +400° F (+205° C) for continuous use in static measurements.

SELF-TEMPERATURE COMPENSATION: See data curve below.

STRAIN LIMITS: Approximately 5% for gage lengths 1/8" (3.2mm) and larger; and approximately 3% for gage lengths under 1/8" (3.2mm).

FATIGUE LIFE: Fatigue life is a marked function of solder joint formation. With 30-AWG leads directly attached to gage tabs, fatigue life will be 10⁶ cycles at ±1500μ"/" (μm/m) using M-Line 358-25 Solder, and 10⁵ cycles at ±1500μ"/" (μm/m) using M-Line 361-20R Solder.

CEMENTS: Compatible with M-M Certified M-Bond 200, but it will normally not provide the greatest fatigue life. Micro-Measurements' M-Bond AE-10/15, M-Bond GA-2, M-Bond 600, and M-Bond 610 are excellent. M-Bond 610 is the best choice over the entire operating range. Refer to M-M Bulletin A-142 for information on bonding agents, and Bulletin B-127, B-130, and B-137 for installation procedures.

SOLDER: If operating temperature will not exceed +300° F (+150° C), M-Line solder type 361 (63-37) tin-lead solder may be used for lead attachment. M-Line solder type 450 (95-5) tin-antimony is satisfactory to +400° F (+205° C). When solder turrets (Option S) are supplied on these gages, they are formed with +570° F (+300° C) lead-tin-silver-solder alloy. Refer to M-M Bulletin A-132 for further information on solders, and Bulletin TT-127 and TT-128 for lead attachments technique.

BACKING: The backing of CEA Series Gages has been specially treated for optimum bond formation with all appropriate strain gage adhesives. No further cleaning is necessary if contamination of the prepared surface is avoided during handling.

FORM: 82-504
CODE: 842016

