

TrueStructures™

Strain Analysis System

Operator's Manual and Sample Lab Procedures



TrueStructures™ Strain Analysis System shown with I-Beam, Torsion Tube and Airfoil Test Sections.

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Introduction to Strain Data Acquisition and Analysis

In this session (which will include Lesson #1: Introductory Measurement Exercise on Page 6), we will familiarize ourselves with the TrueStructures™ System. The knowledge gained will be the basis for all future analysis opportunities.

The System is comprised of the following components;

Rigid Frame

The frame of the system is a very rigid steel structure which will provide the proper strength to support the experimentation without deflection. It is designed to accommodate a number of basic structural members for analysis. **NOTE: See page 7 for caster adjustment photo if unit is on uneven floor.**

Test Structures

The TrueStructures™ System includes the following structures for analysis:

I-Beam: A very capable basic load supporting structure.

Tube: A very important configuration for structures and drive shafts.

Aircraft Airfoil: An advanced structure building on the basic I-Beam and Tube analysis.



TrueStructures™ Lab Test Sections/Components

Note: The aircraft airfoil used in this lab is actually half of a horizontal stabilizer from a production aircraft. While the structure is essentially the same as an aircraft wing, the size allows the system to comfortably fit in the test frame and makes it more affordable.

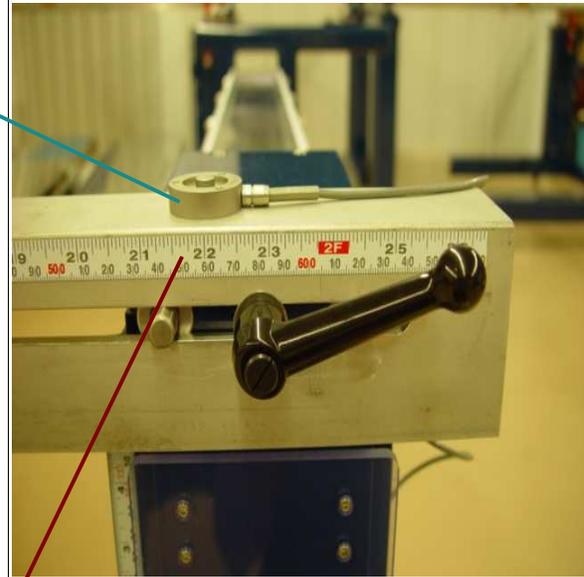
Load Cell Point Load Applicator

Utilizing a crank mechanism and adjustable position load cell, a force or load can be applied to the structure specimen.

- In regards to the wing structure, the force can be applied anywhere along the end of the wing from the front spar to behind the trailing edge of the wing. This force causes the normally cantilevered position of the wing at rest to take on bending or combination bending and torsional loads that might be encountered in flight, or upon landing.
- In regards to I-Beam and Tube test structures, the point load can be positioned at the centerline of each specimen.

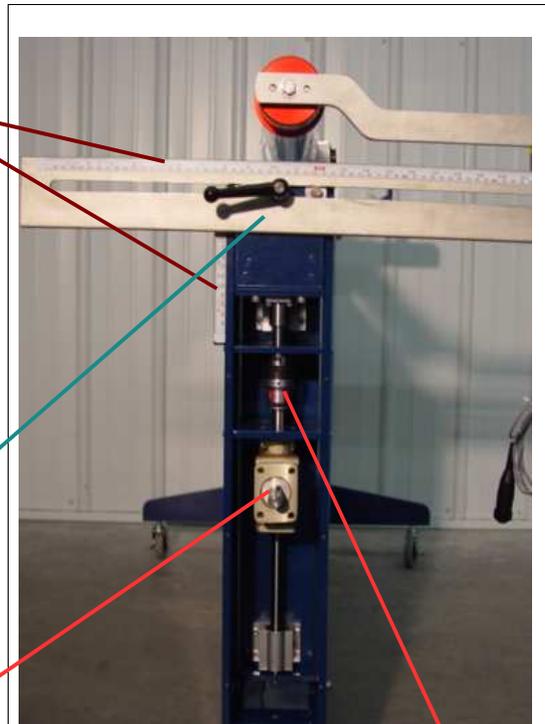
Load Cell

Applies and measures force applied to test specimen. Signal sent to Strain Bridge Controller for display.



Position Scales

Graduated scales applied to the frame. Indicates position of Load Cell Point Load Applicator along x-axis and deflection of test specimen due to loading along y-axis.



Adjustable Point Load Position Table

Enables load cell to be positioned at an infinite number of positions for variable loading scenarios. Utilizes friction clamp to lock table into desired position.

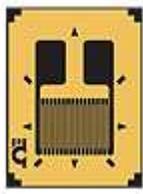


Exposed Right Angle Drive System

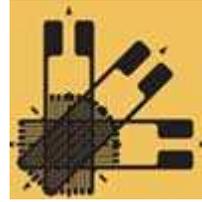
Angle Drive Crank Mechanism-Raises and lowers load cell platform for load application. Includes preset maximum load clutch to prevent system overload.

Strain Gages

Strategically-placed measurement devices used to provide strain data.



Uni-Axial Strain Gage



Tri-Axial Strain Gage Rosette

Strain gages are essentially grid shaped metallic wire, foil, or semiconductor materials that are bonded to the surface they are measuring by a carrier matrix and a thin insulating layer of adhesive. When the carrier matrix is strained, the strain is transmitted to the metallic grid through the adhesive, essentially deforming the grid and changing its electrical resistance. Variations in the electrical resistance of the grid are measured as an indication of strain. Each structural element contains two different types of strain gages: uni-axial and tri-axial rosette style (as pictured above). Each lesson will illustrate the structure being tested along with the location, type and identification letter of each individual strain gage.

Strain Bridge Controller (“Data Box”)

This handy little box houses a number of functions that allow you to accomplish the task of measuring strain in your structure. Touring the face you will see:

Wheatstone Bridge Circuit: Diagram of integrated voltage measurement device used to determine actual strain voltage output (see page 9 for details).

Top Panel Meter: Displays amount of load applied to the structure through Load Cell Point Load Applicator. If MENU button is inadvertently hit, continue pressing MENU Button until the word RESET appears. **Peak Button: Tare (Zero)**

Bottom Panel Meter: Displays the unloaded and loaded voltages of each strain gage.

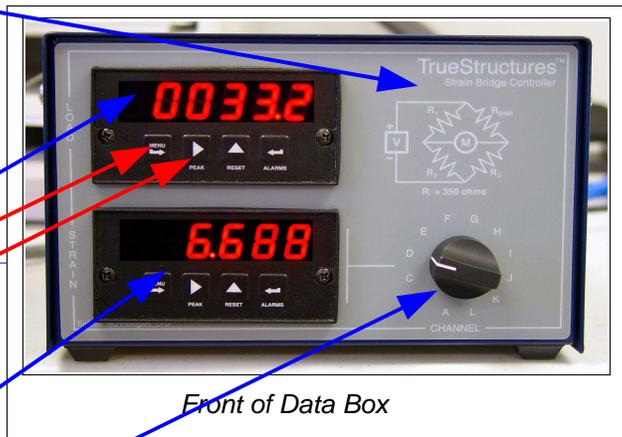
Channel Knob: Allows display of each strain gage voltage individually.

Analog Voltage Output Ports

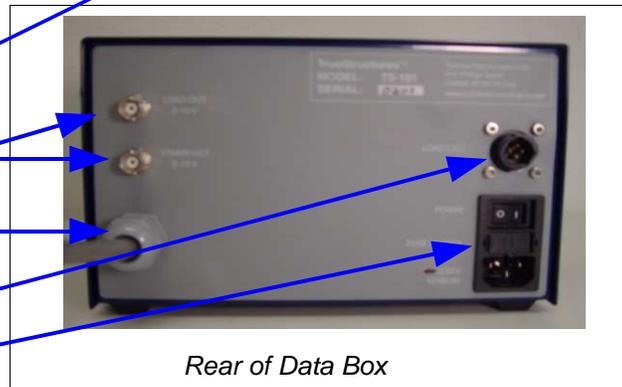
Strain Gage Multi-Pin Cord Entry

Load Cell Connection Port

Power Switch/Power Cord



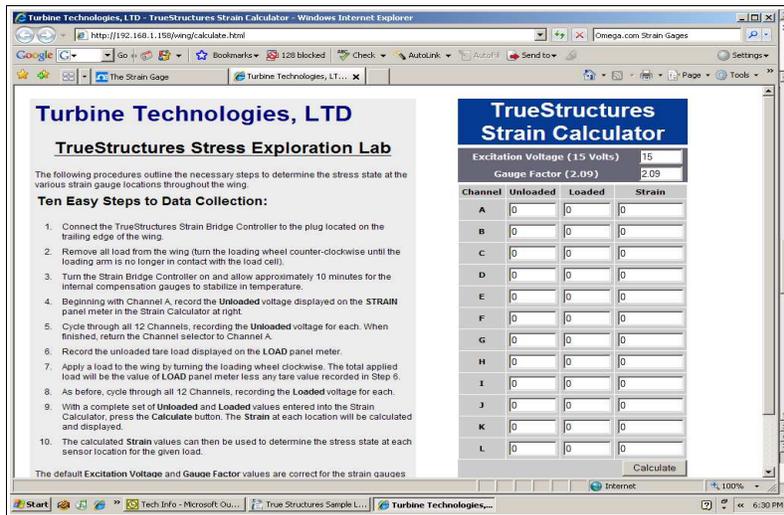
Front of Data Box



Rear of Data Box

Strain Calculator

Allows you to enter the unloaded and loaded voltage values from each strain gage. It automatically calculates the strain value for each channel. **Supplied on disk with manual.**



LESSON #1: Introductory Measurement Exercise

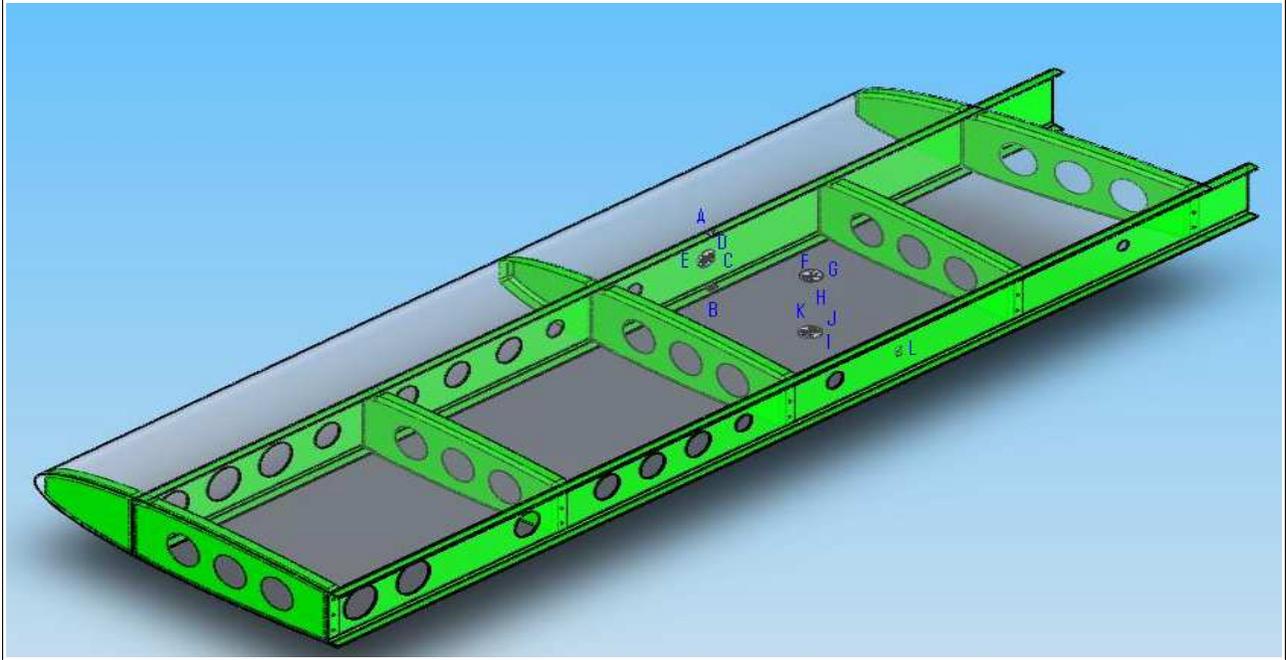
For this exercise, we will use the TrueStructures™ Airfoil (Wing) Section. If the wing is not installed, please install it as shown.



Position wing to align spar ends with fixture tangs.



Finger tighten knobs. Lift up on cantilever end of wing to remove any sag in system. Tighten knobs firmly while continuing to lift end of wing. Be sure load cell and strain gage connections to strain bridge controller (data box).



*Aircraft Structure and Strain Gage Placements
(Please See Page 26 for location reference.)*

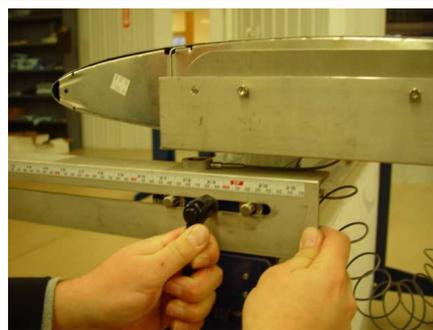
Step 1. Turn on the Strain Bridge Controller and let it acclimate (This is Important). You want all internal resistors to stabilize. Allow 10 minutes for warm up.

Step 2. Bring up Strain Calculator on your computer.

NOTE: Because of the weight of the wing test section, there is play in the end of the wing after it is secured on the capture end. Before you start the test, lift up on the free end of the wing to remove any remaining “sag” and then crank up the load cell to the point of application so that it just touches the wing bottom. This will give you a more accurate starting point and deflection amount. **Press PEAK button on Load Meter to “Tare” or Zero the meter.**



Lift to remove any sag.



Loosen lock to position load cell.



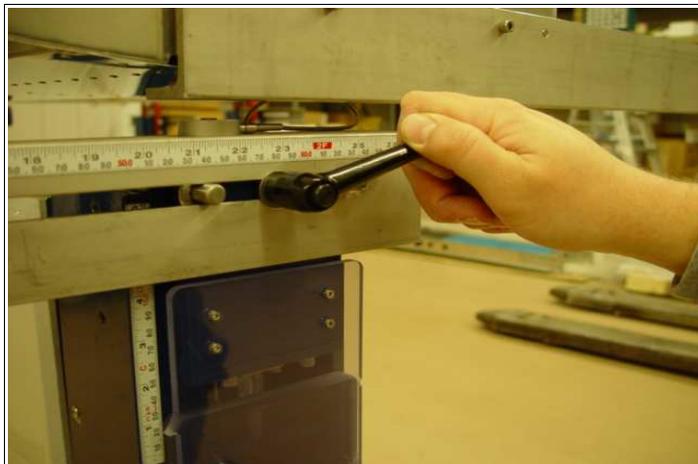
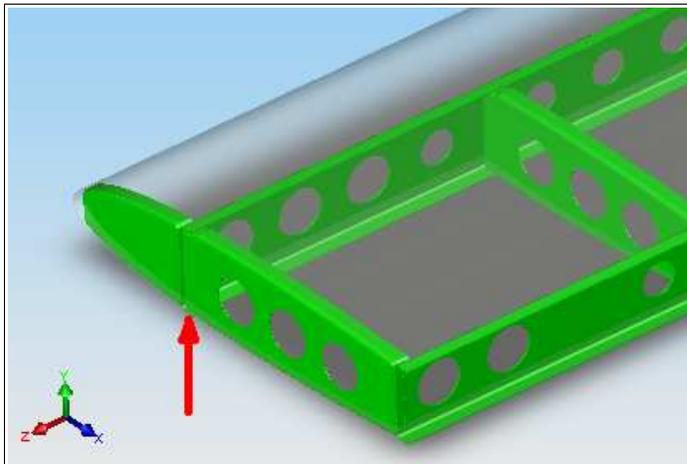
Caster Adjustment.

Step 3. After system has stabilized, record the at-rest voltage levels of each strain gage. This is accomplished by turning the channel knob to each strain gage channel (A-L), displaying the value of each channel in the lower panel meter. The location and corresponding letter of each strain gage is labeled in the illustration. Enter these channel values into the corresponding value windows in the Strain Calculator. **NOTE: If wing sag causes interference with load table during the “at rest “ cantilever check, please release load table lock knob and pull load table off.**

Step 4. Now, add a load to the system (replace load table if it was removed in the last step). This is accomplished by loosening the friction lock and sliding the Load Cell Point Load Applicator until it is positioned directly under the point of interest. In this exercise, position it in the middle of the front spar of the wing (see below).

Step 5. Tighten the friction lock.

Step 6. Make note of the value indicated on the load panel meter (top display of controller). Using crank handle, start cranking clockwise to add a load to the wing end-plate structure. For this exercise, add a net 50 pounds (compensating for any initial value on the display).



Front Spar Load Application Position



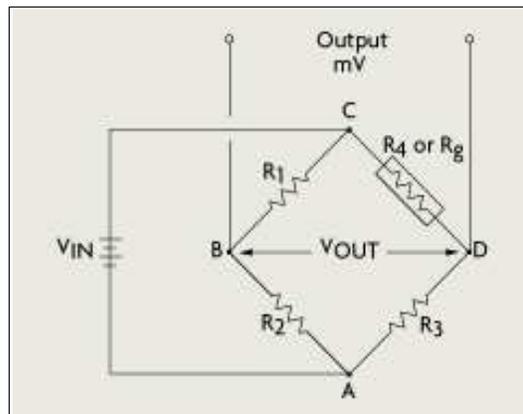
Taking readings from front wing spar loading.

Step 7. Allow the system to settle for a minute. Now record the loaded voltage levels of each strain gage by turning the channel knob to each strain gage channel (A-L) and entering the value of each channel displayed on the strain panel meter into the corresponding value window in the Strain Calculator.

Step 8. Once you have gathered all of the unloaded and loaded channel data, hit CALCULATE at the bottom of your Strain Calculator. All of the strain values for each channel (each strain gage) are calculated for you. Save this data.

Where did these numbers come from?

Let's start with the basics. We mentioned our **Wheatstone Bridge Circuit** earlier when describing the Strain Bridge Controller (Data Box).



Wheatstone Bridge Circuit

A known input voltage feeds four resistors in the system: If all four resistors have the same resistance, the output voltage (V_{out}) will match the input voltage (V_{in}) in a balanced circuit.

In our situation, 3 known resistors of 350 Ohms are fixed in the box while the fourth resistor to round out the bridge circuit is the particular strain gage the channel knob has currently selected. The shape of the strain gage (whether at rest or in a compressive or tensile loading condition) causes a certain resistance value, which changes the voltage output of the bridge circuit. As the gage is strained, its resistance changes, changing the output voltage of the circuit.

The change in resistance of the strain gage and resultant unbalanced voltage output of the bridge circuit is the basis for strain measurement data.

$$V_{out} = V_{in} [R_3/(R_3 + R_g) - R_2/(R_1+R_2)]$$

Manufacturers of strain gages build in certain characteristics which allow steady, reliable readings from their strain gages. Gage Factor is one of those items. Essentially, the Gage Factor relates the ratio of the change in resistance with respect to initial resistance directly to the Strain Value. This is also known as strain sensitivity.

$$GF = \frac{\Delta R_g}{R_g} / \epsilon$$

Where ΔR_g = strained value of gage resistance

R_g = unstrained value of gage resistance

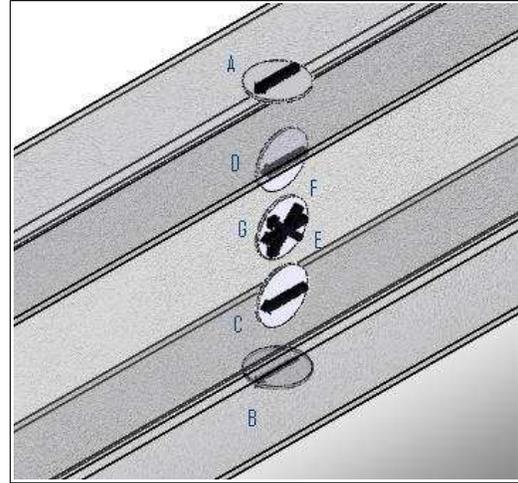
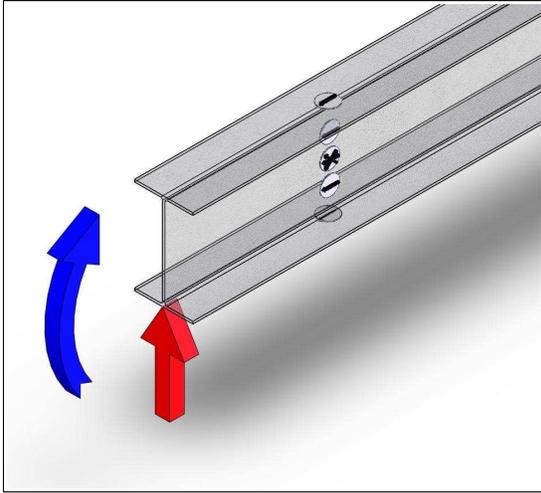
ϵ = Resulting Strain

The Gage Factor for your systems strain gages is shown on your Strain Calculator.

Now you have a feel for how to gather strain data and where the numbers come from. However, jumping into an analysis of an aircraft wing is sort of like jumping right into your PhD in engineering right out of high school. In the next couple of lab sessions, we'll analyze some basic structures to gain a fundamental understanding of the primary elements of strain on a structure. This will allow you to better understand the analysis of an aircraft wing.

LAB SESSION #2 The I-Beam in Bending

In this session, we will analyze a standard 6061-T6 Aluminum I-Beam using the TrueStructures™ System to place a pure bending load on it.

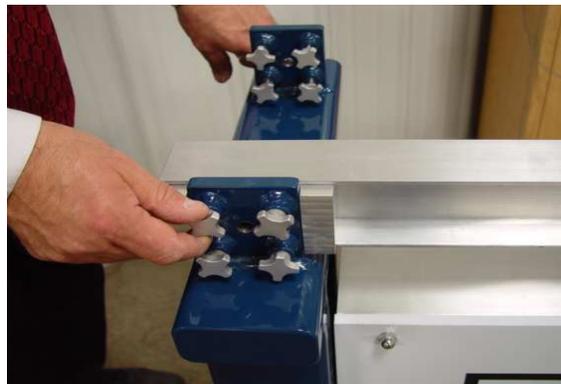


Loading and Strain Gage Placement/Identification

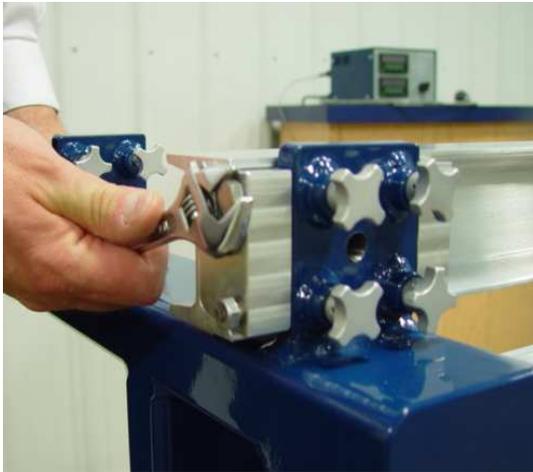
Setup Note: I-Beam should be mounted in the frame and strain gages electrically connected to the Data Box as shown below. If another element such as the Wing or Hollow Circular Shaft is currently in the frame, it should be carefully removed and stored.



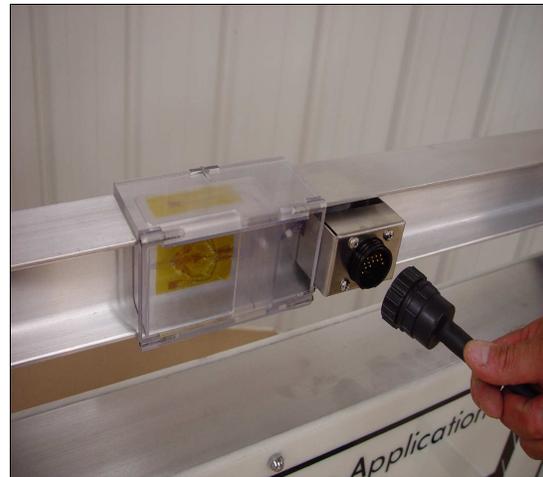
Position I-Beam Assembly Into Frame



Apply and finger tighten connection knobs. Pull up on cantilever end of beam to remove any sag and tighten knobs while pulling up on beam.



Tighten end bolts for sag-free connection.



Plug in Data Box Multi-Pin Connector

Turn the system on to allow acclimation (allow 10 minutes).



Position load cell under center of I-beam

Step 1. Position the load cell directly under the central vertical axis of the I-beam. Tighten friction clamp.

Step 2. Open up Strain Calculator on your computer. Record the unstrained values of each strain gage.

Step 3. Crank load cell up until it touches the bottom of the beam; note vertical position on deflection scale. Load reading display should read zero. Now crank in 50 lbs of load. Note new vertical position on scale (this is your tip deflection).

Step 4. Read and record the strain values of each strain gage into the Strain Calculator. Hit calculate to give you the strain values. Save your results.

Step 5. Measure the beam cross section and determine its Area Moment of Inertia. Why do we need to know this?

Step 6. Calculate the Section Modulus for the I-Beam (provide just a neutral axis calculation for this step to show your methodology). Why is this important?

Step 7. Determine the Modulus of Elasticity? Why is this important?

Step 8. Draw the Load, Shear and Bending Diagrams for this scenario.

Step 9. Calculate the theoretical normal stresses due to bending at each mid-span uni-axial strain gage location. Where do the highest normal stresses occur: web or flanges?

Step 10. Now, use your answers from Step 9 to calculate the theoretical normal strains at each uni-axial strain gage location.

Step 11. Compare actual strain readings to theoretical calculations by plotting those values against the corresponding uni-axial strain gage positions on the I-Beam.

Step 12. Let's now consider our shear stresses due to bending. Calculate the theoretical shear stresses at each mid span uni-axial strain gage location and at the neutral axis of the beam (where is neutral axis and how is it determined?)

Step 13. Plot these values to show a shear distribution on the I-Beam. Where does a majority of the shear stress occur; web or flanges?

Advanced Analysis

Step 14. Using the readings from the rosette strain gages, determine the shear strain at the neutral axis. You will want to use the rosette equations developed for your particular rosette strain gage configuration (rectangular) and then utilize Mohr's Circle to plot the principle strains. How do your measured shear strains compare with the results of the theoretically calculated shear strains?

Extra Analysis

Step 15. Based on the loading, what is the shear flow of this beam cross-section? What is the consequence of shear flow in this particular application?

Lab Session #3 Hollow Shaft (Tube) Analysis

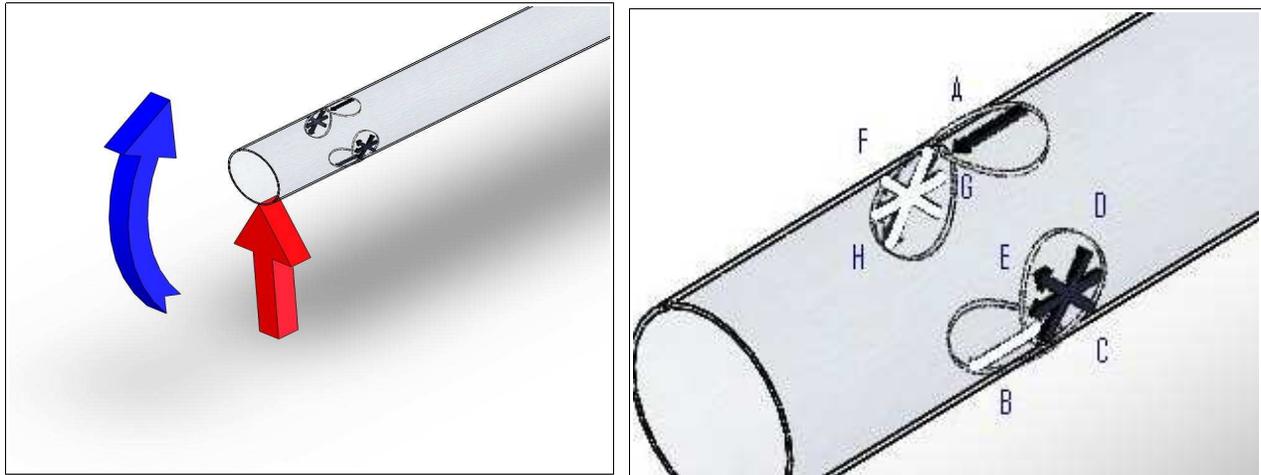
In this session, we will analyze a standard 6061-TL Aluminum tube using the TrueStructures™ System to place it in:

- pure bending
- pure torsion
- combination bending and torsion.

Hollow circular shafts (tubes) are used in static, rigid structures such as tubular bicycle frames and in dynamic, power transfer structures such as drive shafts. A good basic understanding of the load carrying capabilities of a tube will provide insight into more complicated structures such as an aircraft wing.

Exercise A: Pure Bending Analysis

Place the hollow shaft in pure bending.



Loading and Strain Gage Placement/Identification

Setup Note: Hollow Shaft should be mounted in the frame and strain gages electrically connected to the data box as shown below. If another element such as the Wing or I-Beam is currently mounted in the frame, it should be carefully removed and stored. Please see the appropriate section of this manual for installation and removal instructions of any particular test section.



Position tube on frame as shown.



Secure block end with capture knobs while pulling up on cantilever end to remove sag.



Insert Cantilever Load Block on red end.



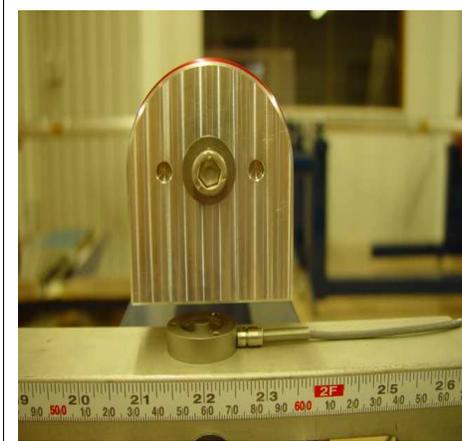
Tighten Load Block with Allen Wrench.

Turn the system on to allow acclimation (allow 10 minutes).

Step 1. Measure the hollow shaft cross section and determine its Area Moment of Inertia. Why do we need to know this?

Step 2. Determine the Modulus of Elasticity? Why is this important?

Step 3. Calculate the Section Modulus for the the Hollow Shaft. Why is this important?



Position load cell at tube centerline.

Step 4. Position the load cell directly under the central vertical axis of the Hollow Shaft.

Step 5. Open up Strain Calculator on your computer. Record the unstrained values of each strain gage.



Taking readings.

Step 6. Crank load cell up until it touches the bottom of the tube. Note vertical position on scale. Load reading display should read zero. Now crank in 50 lbs of load. Note new vertical position on scale (this is your tip deflection).

Step 7. Read and record the values of each strain gage into the strain calculator. Hit calculate to give you the strain values. Save your data.

Step 8. Draw the Load, Shear and Bending Diagrams for this scenario.

Step 9. Calculate the theoretical normal and shear stresses due to bending at each mid-span strain gage location.

Step 10. Now, use your answers from Step 9 to calculate the theoretical normal and shear strains at each strain gage location.

Step 11. Compare actual strain readings to theoretical calculations by plotting those values against the corresponding strain gage positions on the tube.

Advanced Analysis

Step 12. Use Mohr's Circle Analysis to verify the above calculations and to plot the resulting bending and shear strains at each strain gage rosette mounted on the neutral axis of the tube. Verify the corresponding bending and shear stresses from this analysis and compare with the theoretical values calculated. These results will be important as comparison values for future loading of the tube in pure torsion and finally compound bending and torsion of the tube.

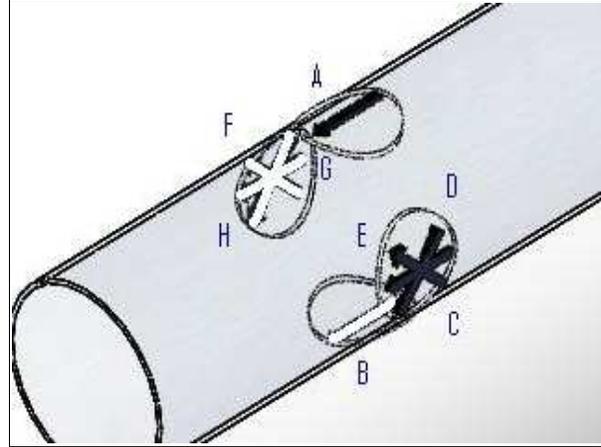
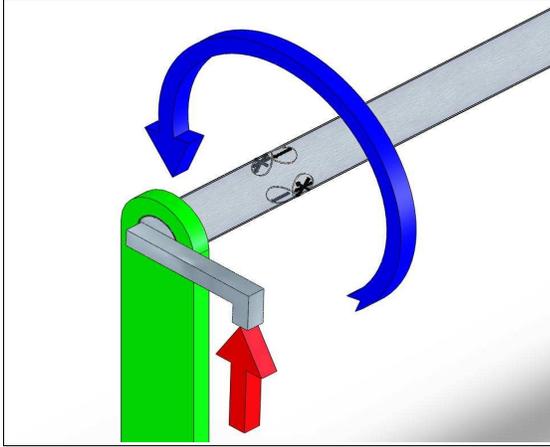
Extra Analysis

Step 13. Compare the resulting loading, stress, strain of the tube with that of the I-Beam for the applied load. What conclusions can be drawn from the analysis regarding suitability of a Tube versus I-Beam for a cantilever bending situation?

Step 14. Based on the loading, what is the shear flow of this tube cross-section? What is the consequence of shear flow in this particular application?

Exercise B: Pure Torsional Analysis

This exercise will apply pure torsional loading to a typical circular drive shaft which is restrained from bending on both ends. We are concerned with Shear Stress and Shear Strain in torsion with this type of shaft configuration.

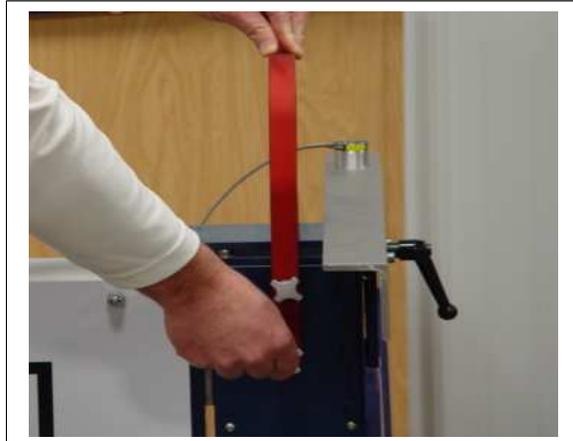


Loading and Strain Gage Placement/Identification

Setup Note: Hollow Shaft with Torsion Yoke End will be mounted in the frame and strain gages electrically connected to the Data Box. If the Wing or I-Beam is currently mounted in the frame, it should be carefully removed and stored. If you still have the tube mounted in the structure in the cantilever position with the load block on the end from the previous exercise, remove the load block, then remove the tube from the frame, reversing the process shown in the previous exercise (Exercise A). Then follow the new instructions below:



Position Yoke on Crank End (note correct face out as marked)



Align with frame holes and loosely secure with capture knobs (do not tighten yet).

NOTE: Turn the system on to allow acclimation if it has been off (allow 10 minutes).



Slide red end of tube into yoke. Push in fully.



Tighten block end knobs fully. Then tighten red yoke knobs securely.



Position guide pins and slide on Torque Arm



Tighten Torque Arm Bolt securely with Allen Wrench.



Position Load Cell to desired moment arm dimension from tube centerline (Step 2).



Crank in load and take readings on each channel (Steps 3, 4, 5) .

Step 1. Measure the hollow shaft cross section and determine its Polar Moment of Inertia. What is Polar Moment of Inertia and why do we need to know this?

Step 2. Position load cell directly under the torsional loading arm axis of the Hollow Shaft as shown. Measure and record the moment arm from center of Hollow Shaft to load cell application point.

Step 3. Open up Strain Calculator on your computer. Record the unstrained values of each strain gage.

Step 4. Crank load cell up until it touches the bottom of the torsional loading arm; note vertical position on scale. Load reading display should read zero. Now crank in 50 lbs of load.

Step 5. Read and record the values of each strain gage into the strain calculator. Hit calculate to give you the strain values. Our main focus for this exercise will be the strain gage rosette.

Step 6. Sketch the loading diagrams for this scenario.

Step 7. Determine the Shear Modulus of Elasticity? Why is this important?

Step 8. Calculate the Maximum Torsional Shear Stress experienced by the shaft under this loading. Why is this important?

Step 9: Let's analyze the shear strain of our hollow shaft using Mohr's Circle as it applies to our rosette strain gage. The analysis is based on the clock-wise orientation of the rosette as positioned along the straight outer skin line. We use a rosette to compute the state of strain at that particular point. The resulting Mohr's Circle plot gives the value and orientation of the principle strains. The uni-axial strain gages react only to the shear stress in this configuration (as there is no bending). It will be important to compare the differences in the uni-axial strain gage readings with our next configuration (combination loading).

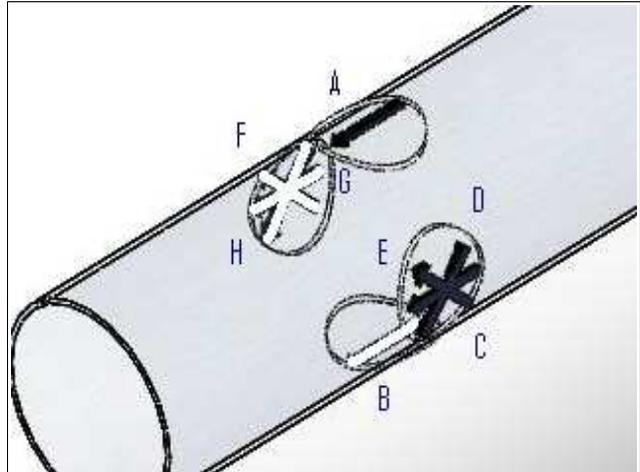
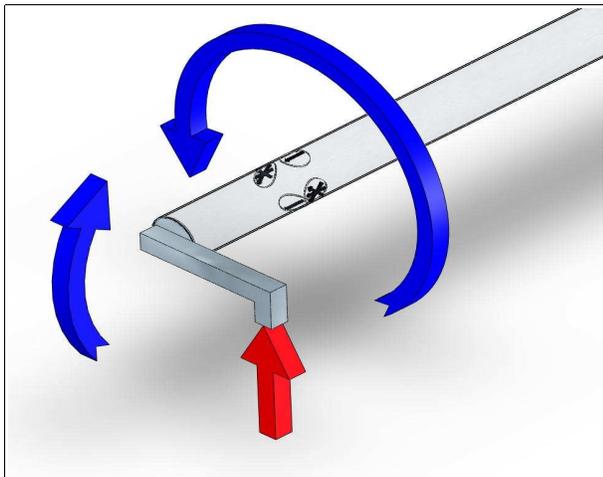
Additional Analysis

Step 10. Let's calculate the torsional deflection (twist) of the shaft between the strain gage location and applied torque position for the loading shown.

Step 11. Shear Stresses due to torsion on a closed element such as a hollow shaft or tube act around its cross-sectional perimeter. This is known as the Shear Flow for this configuration. Calculate the Shear Flow for the tube with current loading.

Exercise C: Combination Loading: Bending and Torsion

For this exercise, we will remove the torsional end Yoke from the pure torsion configuration to return the hollow circular shaft (tube) to a cantilever configuration. We will load the tube in torsion, as in Lesson B. However, as you will see, the tube will now absorb combination bending and torsion, a more demanding load configuration. This cantilever configuration will be compared with the previously restrained configuration to show the differences in these two scenarios.



Loading and Strain Gage Placement/Identification

Setup Note: Tube should be mounted in the frame and strain gages electrically connected to the data box according to the Operators Manual. If another element such as the Wing or I-Beam is currently mounted in the frame, it should be carefully removed and stored.

Important: Please be sure torsional end Yoke is removed from load end of tube before starting this analysis. Please follow these removal instructions:



Loosen Torque Arm with Allen Wrench and remove.



Loosen capture knobs on capture block end and slide tube out of yoke.



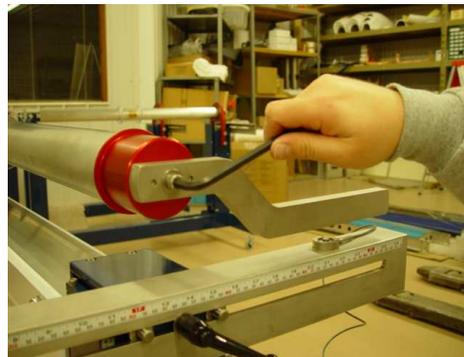
Loosen capture knobs, remove yoke.



Position tube in cantilever position, tighten hand knobs while pulling up on tube end..



Insert Torque Arm into Tube End.



Tighten Arm with Socket Wrench, then position Load Cell.

Turn the system on to allow acclimation if it has been off.

Step 1. Record the Polar and Area Moments of Inertia for the tube cross-section. Why do we need both of these?

Step 2. Position the load cell directly under the torsional loading arm axis of the Tube as shown. Measure the moment arm from center of Tube to load cell application point (use the same value as the previous exercise).

Step 3. Open up Strain Calculator on your computer. Record the unstrained values of each strain gage.

Step 4. Crank load cell up until it touches the bottom of the torsional loading arm; note vertical scale position Load reading display should read zero. Now crank in 50 lbs of load.

Note: If there is some sag in the test section, pull up on red end of tube to remove the sag. While holding the tube in this spot, position the load cell so it just touches the bottom of the torque arm. Start your test from this position.

Step 5. Read and record the values of each strain gage into the strain calculator. Hit calculate to give you the strain values. Unlike pure torsion, where our main focus was the strain gage rosettes, we will be very interested in all gages because of the added bending due to cantilever state of the hollow shaft

Step 7. Determine the Bending and Shear Modulus of Elasticity? Why do we need both?

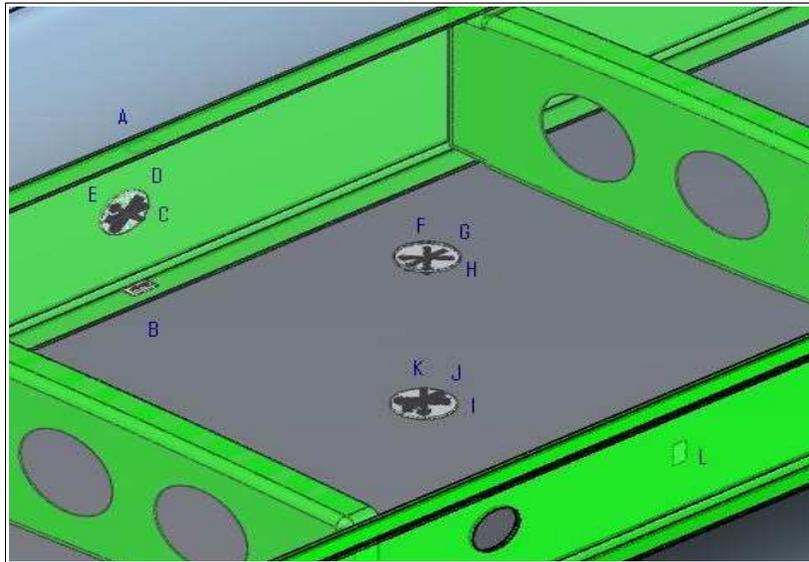
Step 8. Sketch the loading diagrams for this scenario.

Step 9. Calculate the maximum bending and shear stresses for this loading.

Step 10: Let's start by analyzing the new bending and shear stresses and strains of our tube using Mohr's Circle as it applies to our rosette strain gages. Compare your results with the restrained tube in Exercise B. Bending and shear stress now play a role due to the tube being unrestrained at the cantilevered end.

Step 11: Compare the readings of the axial (top and bottom) strain gages of this test verses to the pure torsional test. Based on just this data, what basic conclusion(s) can be drawn between a tube in pure torsion (restrained on both ends) verses a tube subjected to combination torsion and bending (cantilever configuration).

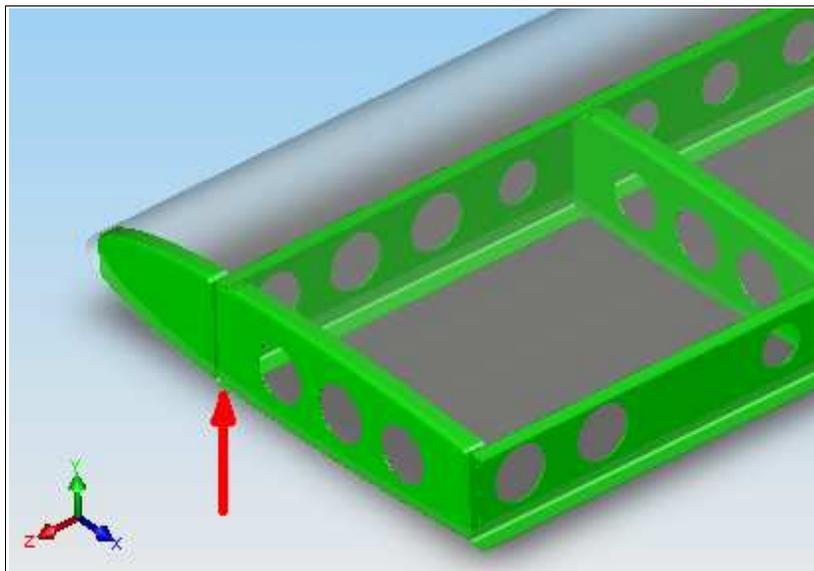
LAB SESSION #4: Wing Strain Analysis



Strain Gage Placement in Wing (See Page 25 for reference location)

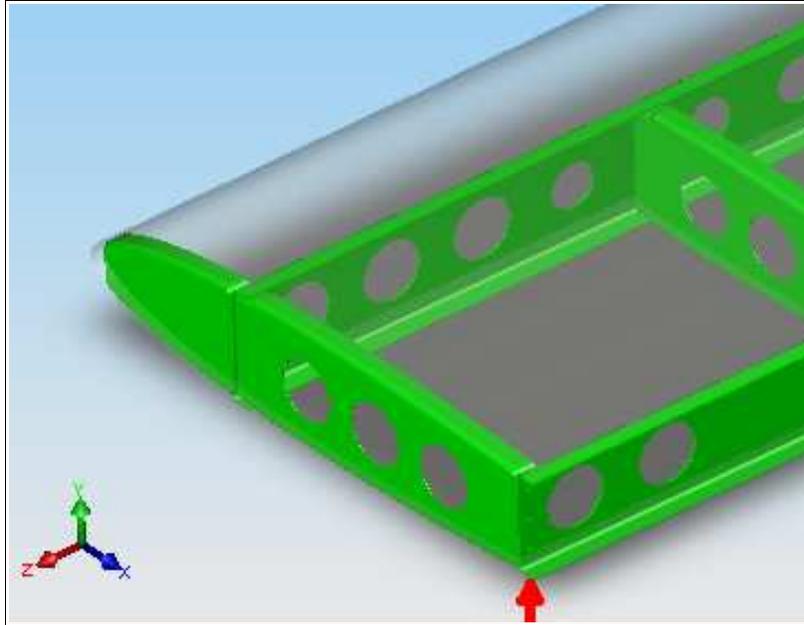
Now that we have some good experience with the TrueStructures™ System, it's time to tackle the wing structure. Using the knowledge gained analyzing the I-Beam and Tube, you can now see that the wing structure is an advanced combination of beams (spars and ribs) and tube (wing skin).

Step 1. Go back to **Lesson #1** and follow the steps outlined in the **Introductory Measurement Exercise**. The load will be 50 lb applied at the centerline of the wing's front spar. Record all the strain data from each channel and save it.



Front Spar Load Position

Step 2. Remove the load from the front spar and apply it to the rear spar centerline, following the same data recording steps.



Rear Spar Load Position

Step 3: Based on the two loading scenarios, compare how the spars and skin are stressed and strained. Use the previous I-Beam and Tube analysis exercises to simplify the basic elements that need to be examined in the wing. State your assumptions and methodology.

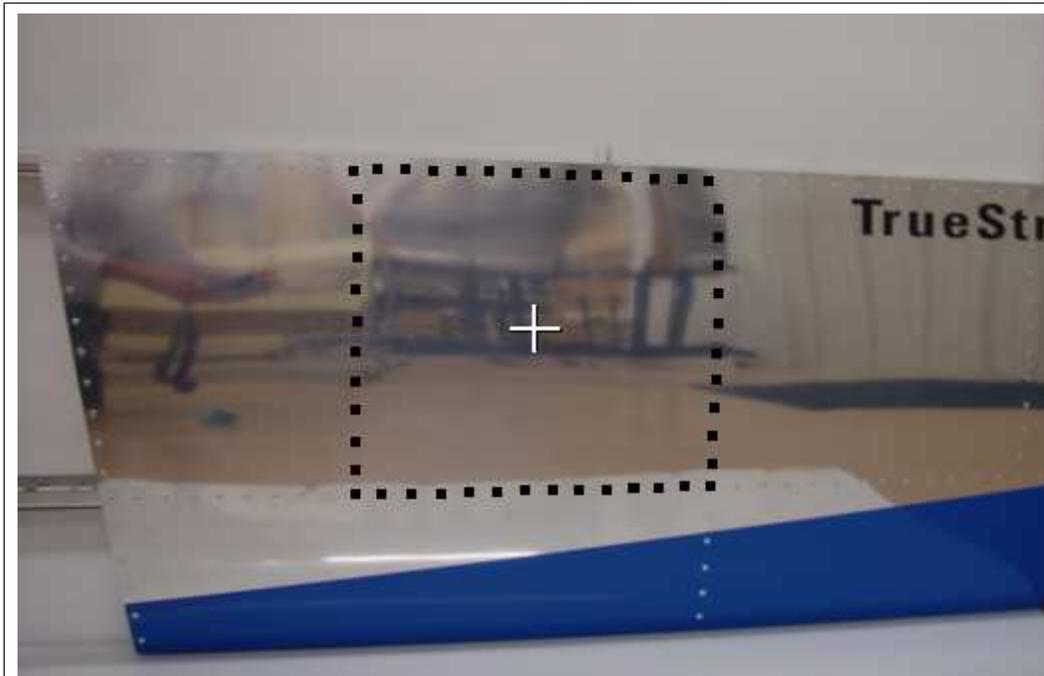
Step 4. For each strain rosette location, use Mohr's Circle to determine the states of stress and strain for each loading scenario (front spar, top and bottom wing skins). Focusing on the front spar rosette results, how do the stress and strain results compare with the corresponding calculations from Step 3?

Additional Analysis

Step 5. If our wing had a landing gear that transferred 50 lb of load upon touchdown the runway, which spar would be better suited to mount the gear to, from a load distribution point of view. Why?

Step 6. With the load positioned at the rear spar, calculate the shear stress and consequent shear flow at: Wing Tip and Strain Gage Placements.

Step 7. With the load positioned at the front spar, calculate the shear flow between spar and skin. What would be the minimum rivet spacing required to maintain this structure at this load with no factor of safety?



Strain Gages are located in the first full bay from spar roots as shown. The two Rosette Strain Gages are located in the center of the bay as indicated by the white hash mark in the photo. An axis indicator is labeled on the back spar for reference (see below)



Rear Spar has an indicated axis line for strain gages location. All strain gages are located on this axis.