

## **Real-Time Data Acquisition and Structural Health Monitoring System**

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# Real-Time Data Acquisition and Structural Health Monitoring System

## Abstract

This paper describes a method for measuring strain and stress values in a real world project through the use of sensors, data acquisition hardware, and the LabVIEW software program. The proposed method describes how real time information about mechanical properties can be gathered within a single user-friendly program.

The ability to make drastic or life-saving decisions during an air mission is an example of a real-world application of this project. The aircrew needs the ability to understand and recognize the mechanical properties of the aircraft components in real time. The proposed method will provide the mechanical properties of the part within a single Excel file. This is similar to the information that a laptop mounted within the cabin of the aircraft, known as a “tough book,” delivers. This information is in turn used for critical decisions in any air missions.

## Introduction

The use of sensors mounted on critical aircraft components has proved to be a reliable method for Structure Health Monitoring (SHM). The main focus of utilizing sensors in SHM is to maximize the chance of detecting system failure or potential damage with a limited number of sensors in real time. The mission success of any air mission depends on making critical decisions by the aircrew and pilots. They utilize real-time information about the aircraft’s status to determine if the time and situation will allow for a successful mission. For example, the failure of the high speed shaft that transfers torque directly to the tail rotor causes loss of power and an unexpected drop in altitude in H-60 Sirkorsky helicopter<sup>1</sup>. The ability for the aircrew, in the cabin of the helicopter, to indicate the failure of the high speed shaft or any other problems, would allow further mission reevaluations. In order to monitor aircraft components, data may be gathered through the utilization of sensors mounted on aircraft components. The data can be transferred to a frame-mounted laptop within the aircraft’s cabin that is accessible by the aircrew.

Researchers from universities and national laboratories have determined the importance of having a monitoring system for overall use in gathering data specific to aircraft health and structural integrity. Dr. Kara Peters<sup>2</sup>, of North Carolina State University, states “if you have enough sensors in there, you could predict an earlier failure in the part.” This application could help aircrew and pilots to understand the real-time health of the aircraft and utilize the information to determine critical mission decisions. Also, Dr. Peters has emphasized the need for a quick turnaround of real time information, stating that, “as the systems change, we have to change how we inspect aircraft to ensure traveler’s safety.”

Also scientists within the Air Force Research Laboratory<sup>3</sup> (AFRL) have been attempting to integrate sensors within the aircraft components for the “crews to monitor the condition of aircraft in real time.” The scientists were able to conduct fatigue test on certain components of

the aircraft under simulated flight conditions and collect the data within a rapid SHM system. The overall goal of the AFRL is to collect mechanical properties of components to aid the aircrew so they will be able to “analyze the inputs to form the most complete picture possible” of the aircraft health during missions.

In this project, precision strain gages are mounted to a loaded aluminum specimen, simulating sensors mounted to aircraft components and acted upon by a force. The real-time signals, received from strain gages, will be in turn transferred to LabVIEW software program in order to calculate and plot strain and stress values. Comparing the relationship of the stress and strain distribution curves proves the effectiveness of the experiment.

## Theory

In order to simulate this process, the theory of pure bending will be utilized to obtain engineering strain values from a specimen under a specific load. Pure bending will allow a section of the specimen to undergo a constant bending moment, due to the absence of shear forces within the specific section. Figure 1 shows a specimen in pure bending set up, as well as the associated shear and moment diagrams<sup>4</sup>. As depicted in figure 1, the constant moment value is located between points B and C. The constant moment value will be used for the experimental test and analytical calculation of the bending stress. Also, the constant shear force between points A and B or C and D will be used for experimental test and analytical calculation of the shear stress.

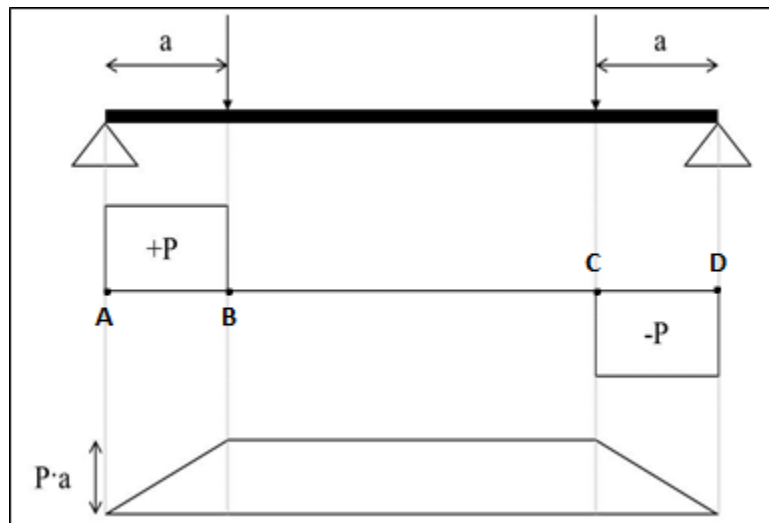


Figure 1. Pure Bending, Shear and Bending Moment Diagrams

The bending stress is determined by Equation 1,

$$\sigma_{\text{bending}} = \frac{My}{I} \quad (1)$$

where ‘M’ represents the bending moment, ‘y’ represents the distance from the neutral axis to the interest cross-section, and ‘I’ represents the Area Moment of Inertia. For a square or rectangular cross-sectional area, the Area Moment of Inertia is represented by Equation 2,

$$I = \frac{bd^3}{12} \quad (2)$$

where, ‘b’ and ‘d’ are the width and the height of the cross-section respectively. Therefore the graphical representations of the strain and the bending stress distributions should reveal linear curves verses y values, shown in Figure 2.

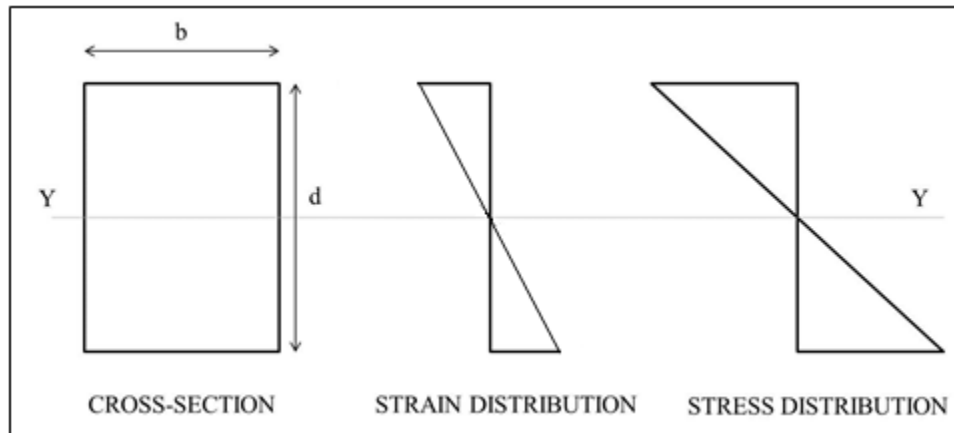


Figure 2. Strain and Stress Distribution

Transverse shear stress ( $\tau$ ) is determined by the following equations:

$$\tau = \frac{VQ}{Ib} \quad (3)$$

$$\tau = G\gamma \quad (4)$$

Where, ‘V’ is the vertical shear force, ‘Q’ is the first moment of area, ‘G’ is shear modulus, and ‘ $\gamma$ ’ is shear strain.

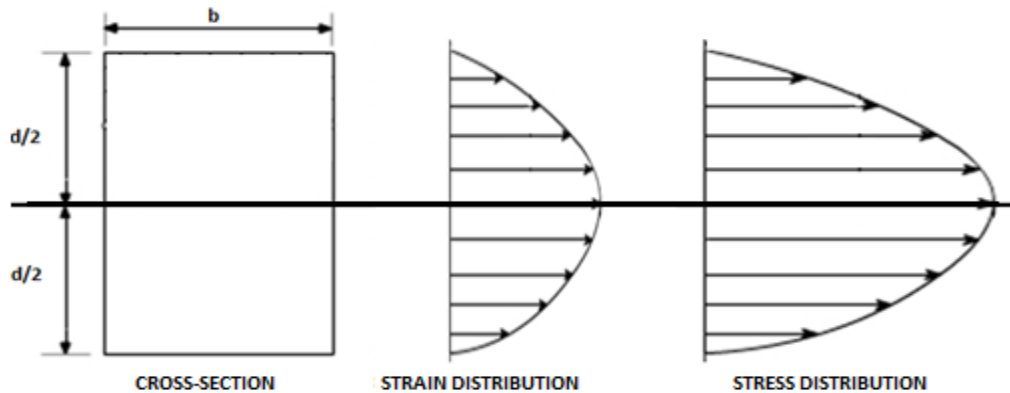


Figure 3. Shear Strain and Stress Distribution

The strain,  $\epsilon_{\theta}$ , in any direction can be determined by equation five.

$$\epsilon_{\theta} = \frac{\epsilon_x + \epsilon_y}{2} + \frac{\epsilon_x - \epsilon_y}{2} \cos 2\theta + \frac{\gamma_{xy}}{2} \sin 2\theta \quad (5)$$

Subtracting two strains in arbitrary angles results in:

$$\epsilon_{\theta_1} - \epsilon_{\theta_2} = \frac{\epsilon_x - \epsilon_y}{2} (\cos 2\theta_1 - \cos 2\theta_2) + \frac{\gamma_{xy}}{2} (\sin 2\theta_1 - \sin 2\theta_2)$$

Let  $\theta_1 = 45^\circ$  and  $\theta_2 = -45^\circ$  provides:  $\epsilon_{\theta_1} - \epsilon_{\theta_2} = \gamma_{xy}$  (6)

Where shear strain can be measured by using equation six.

Figure 4 shows orientations of strain gages to measure normal and shear strains.

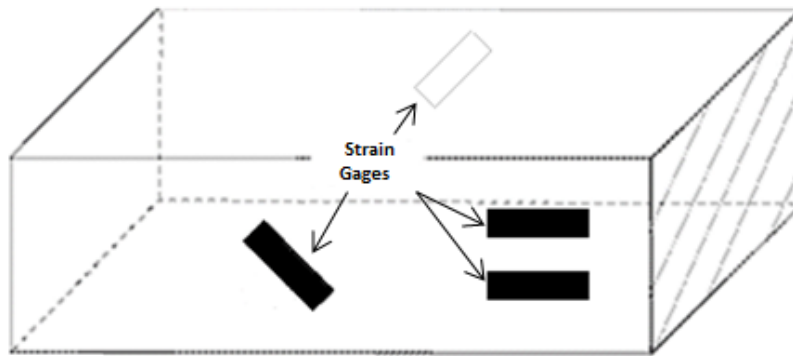


Figure 4. Strain Gage Orientations for Shear Strain and Normal Strain

In this project, the solid rectangular test specimen is used to replicate the main load bearing support in a monospar wing depicted below.

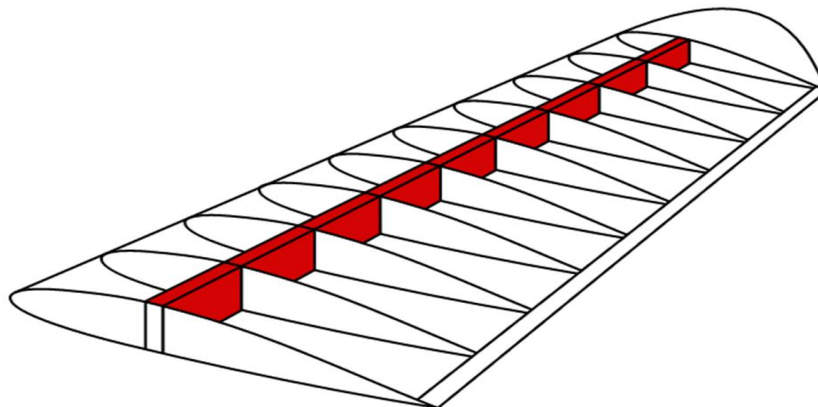


Figure 5. Monospar Wing (Google Image)

## Experimental Set-Up and Procedure

The purpose of this section is to develop an experimental system that makes continuous strain and stress measurements until stopped by the user. Also, the system sends the alert if the stress exceeds the allowable stress. The National Instrument (NI) data acquisition hardware, precision strain gages, two aluminum bars, and LabVIEW software are utilized in this project. NI hardware includes the SCXI-1000 chassis, SCXI-1314 strain terminal block<sup>5</sup>, SCXI-1520 strain module<sup>6</sup>, and NI PCI-6221 data acquisition card installed on a computer.

### a. Developing Software Program

This project starts with developing a LabVIEW program for reading the values of the strain gages. For sake of convenience, two Type J 500  $\Omega$  potentiometers were utilized to manually change the resistance which stimulates strain reading through LabVIEW software. Figure 6 is used as a Half Bridge configuration wiring diagram to connect potentiometers to the signal conditioner. The SCXI-1314 has eight possible channels for strain gage connections.

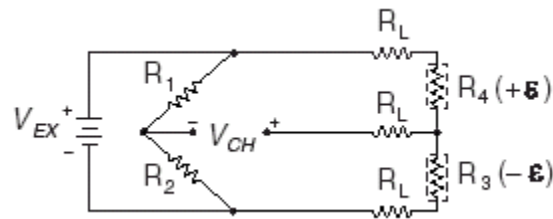


Figure 6. Half Bridge Schematic for SCXI Strain Components

In order for LabVIEW software to integrate with NI data acquisition hardware and read the data, SCXI hardware needs to be virtually installed in LabVIEW environment. The information gathered from the SCXI components appear within the program, by using the data acquisition input command<sup>7</sup>. Figure 7 shows the installation of the SCXI hardware into LabVIEW software. To recognize the input from the SCXI components, the SCXI-1000 chassis has to be located as a “new device” and installed within the “Measurements and Automation Explorer” component of LabVIEW<sup>8</sup>.

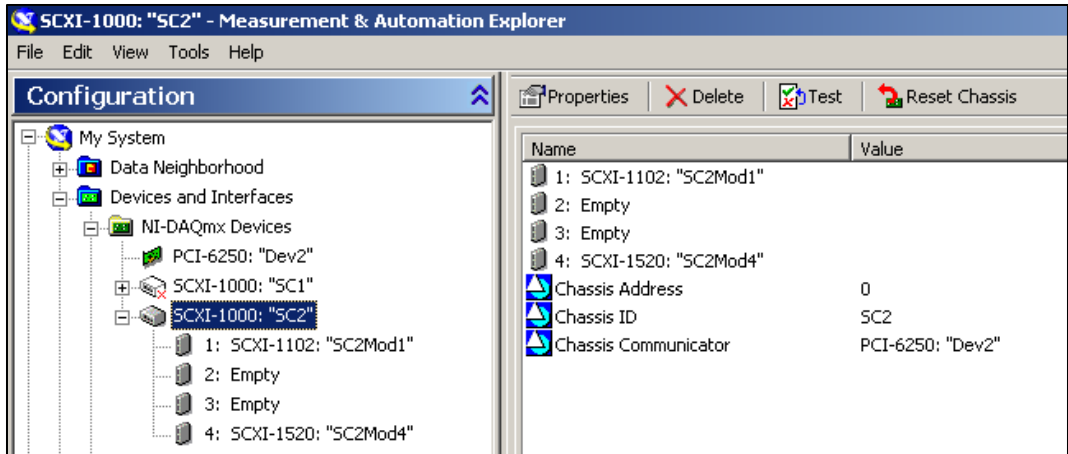


Figure 7. Installation of SCXI hardware into LabVIEW software

Once recognized by the LabVIEW automation software program, the information gathered from the SCXI equipment is then transferred into LabVIEW by using the Data Acquisition (DAQ) input. The data acquisition manipulator can be configured to accept the data signals from the SCXI-1520 module once input is utilized within the LabVIEW program. Specific information, pertaining to the SCXI-1520 Strain Module, will be specified within the DAQ input, such as the single channel used as shown in Figure 8.

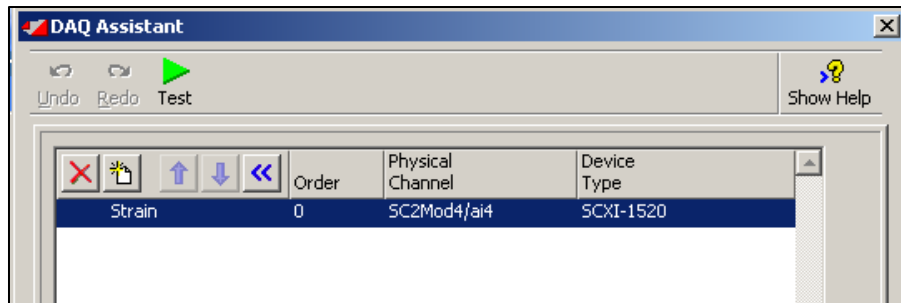


Figure 8. DAQ information specified from SCXI 1520

With the connection and DAQ input set, the testing of potentiometer's wiring can take place. Figure 9 indicates that LabVIEW software has received the signals from the potentiometers. Also, testing the signal and editing initial configuration settings under the DAQ input Express Task, will allow the signal sensitivity to be adjusted, as seen in Figure 9.

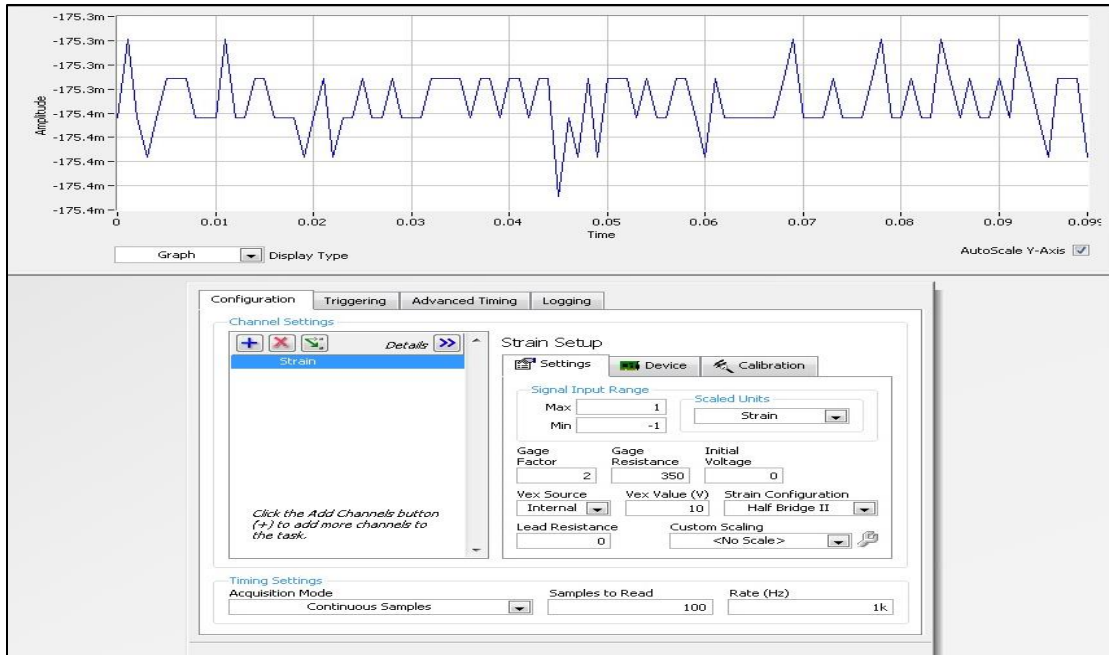


Figure 9. Signal Test and Configuration of DAQ Input

After verifying all aspects of the simulation, the Front Panel within LabVIEW is programmed to read the real-time potentiometer's values, graph the emulated strain values versus time, as well as save all information to a TDMS file to be utilized within an Excel file<sup>9</sup>. Figure 10 shows the Block Diagram and programming for the gaining of the emulated strain values, along with descriptions of each component within the Block Diagram.

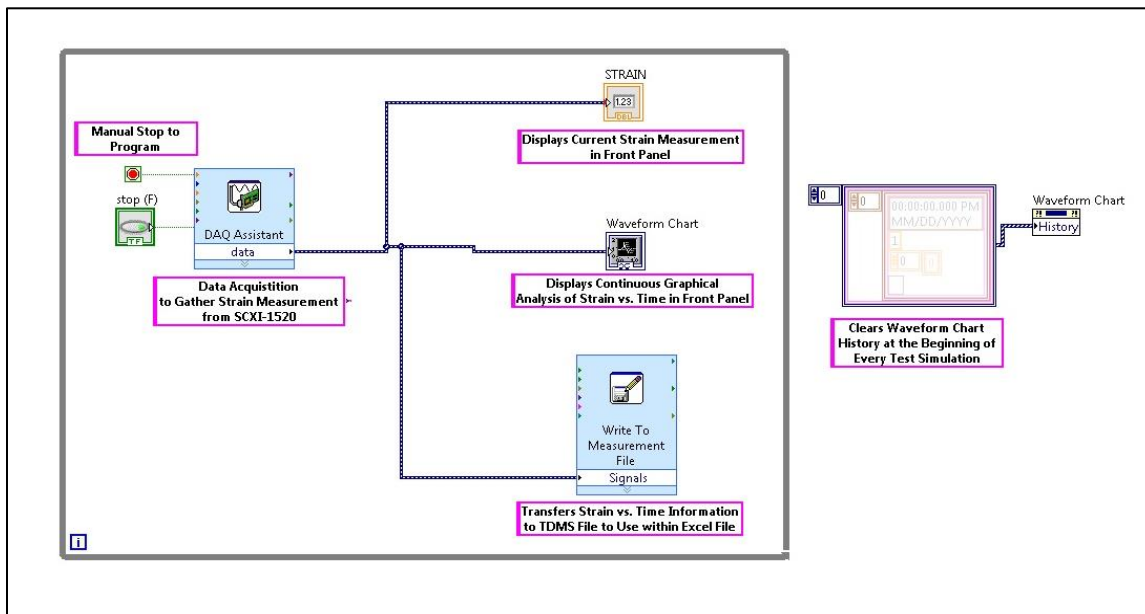


Figure 10. Block Diagram of LabVIEW Programming



After successfully running the program and gathering simulated strain values from potentiometers, the Front Panel reveals the graphical information and the real-time simulated strain values. After the completion of the test run, the TDMS file is then opened within an Excel spreadsheet. With the given information of time and accompanied strain values, a second graph is then created within the Excel file to graphically represent the given information. Figure 11 shows the comparison of the Front Panel to the Excel spreadsheet's graphical data. The identical shapes of two graphs indicate that both graphs represent the same information.

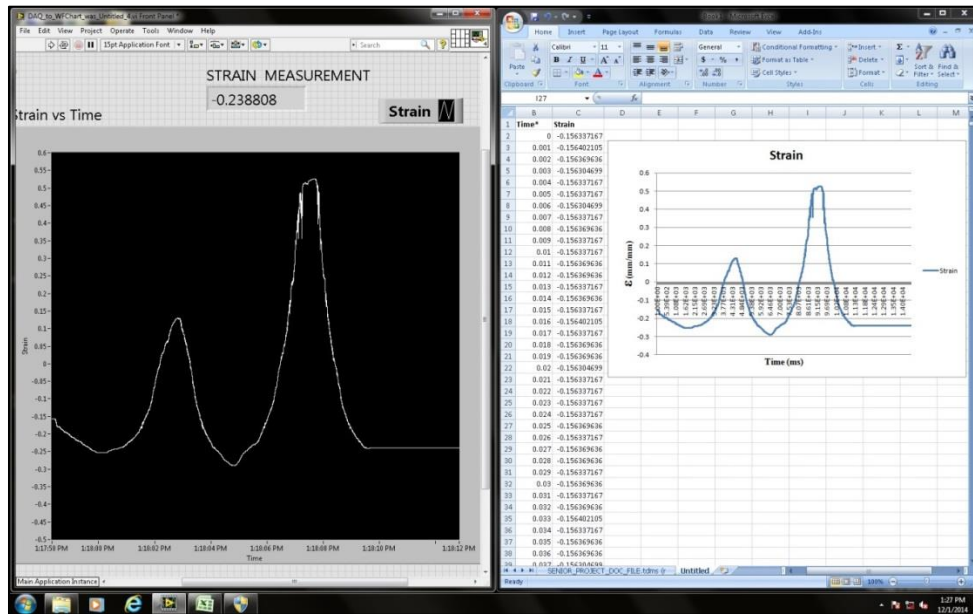


Figure 11. Comparison of Front Panel to Excel

The collected data from potentiometers indicates that the wiring and programming for reading the strain values are accurate.

### b. Attaching Strain Gages

After developing the LabVIEW program for reading strain values, the next step is to attach the strain gages to an aluminum bar and read the strain values. First, seven 350Ω precision strain gages are adhered to the outer surfaces of an 13-1/8” x 1.25” x 1.25” aluminum bar for reading the normal strain values for bending stresses. The Vishay Instruction Bulletin is then used as a guide to attach the strain gages to the bar<sup>10</sup>. Then, eight strain gages are adhered to the surface of an 24” x 4” x 1” other aluminum bar for reading the strain values for shear stresses. The orientation of strain gages are given in figure 4. Figure 12 and 13 shows strain gages after being attached to the outer surfaces of the aluminum bars profile. The ends of negative and positive excitation of each precision strain gage are in turn connected to a channel of National Instrument’s SCXI-1314 Strain module. Also, other strain gages are connected to the other channels with similar connection blocks. Strain values can be collected as result of change in cross-sectional area of the metallic foil wire from the strain gages under a specific load. The

small changes in resistance of the strain gages are typically measured in a Wheatstone Bridge arrangement in NI hardware. Figure 14 shows how a strain gage is wired in the half bridge configuration and is directed to a separate channel within the SCXI-1314, allowing for reading of each individual strain gage's values.

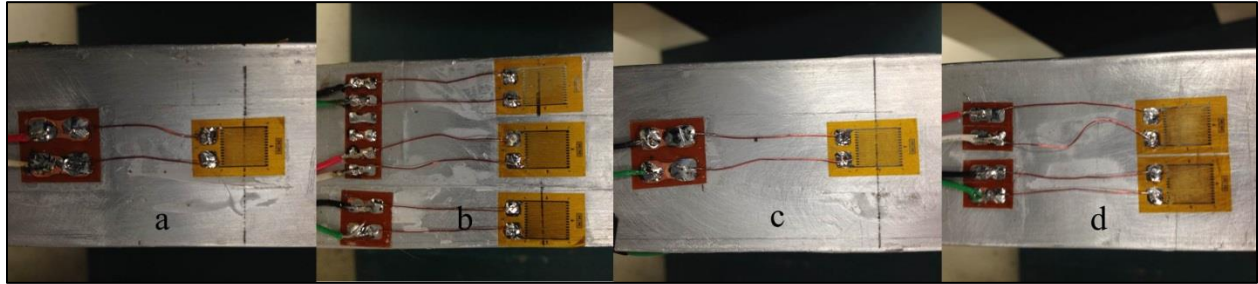


Figure 12. Seven Strain Gages Attached to Aluminum Surfaces for Normal Strain Measurements

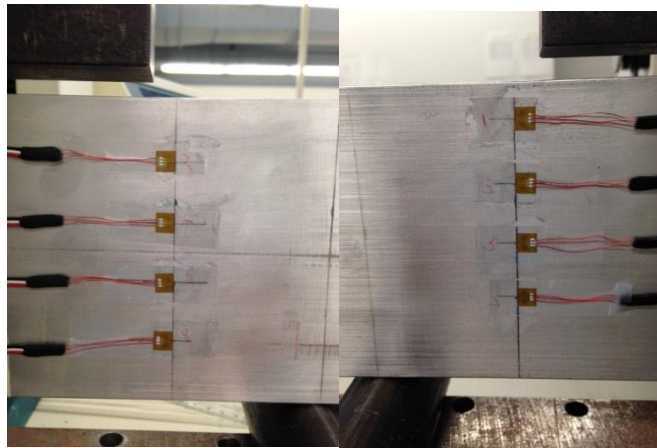


Figure 13. Eight Strain Gages Attached to Aluminum Surface for Shear Strain Measurements

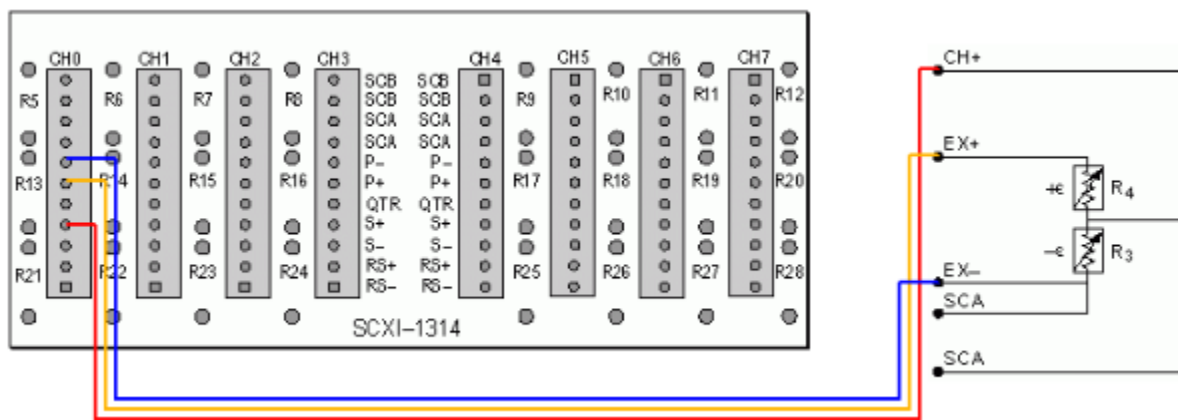


Figure 14. Connection Diagram for Half Bridge Connection

### c. Testing the Aluminum Bar for Measuring Bending Stress

After installing strain gages, the next step is to test the aluminum bar under pure bending condition. Figure 15 shows the set-up experiment for reading normal strain values for bending stress. The top bar accepts the force from the material testing machine and distributes two equal loads to the aluminum bar, three inches away from either side of the bar.



Figure 15. Pure Bending Set-Up for Bending Stress

Figure 16 shows the free body diagram of the aluminum bar under the pure bending criteria.

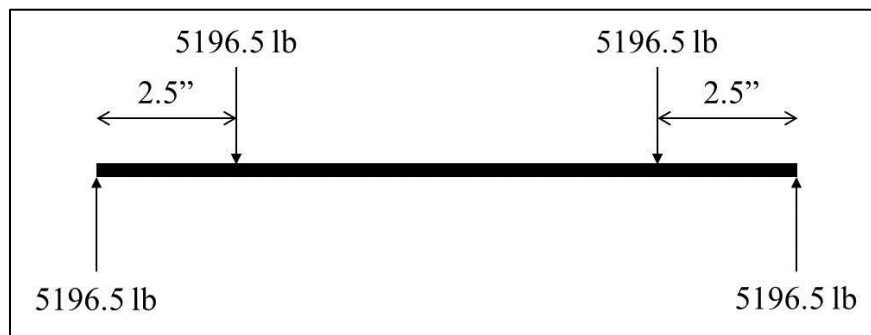


Figure 16. Free Body Diagram of Aluminum Bar

Also, the original LabVIEW program has been modified to accommodate reading of strain and stress from seven strain gages. Stress is calculated by Hooks law for each strain value. Figure 17 shows the LabVIEW program for reading bending stress.

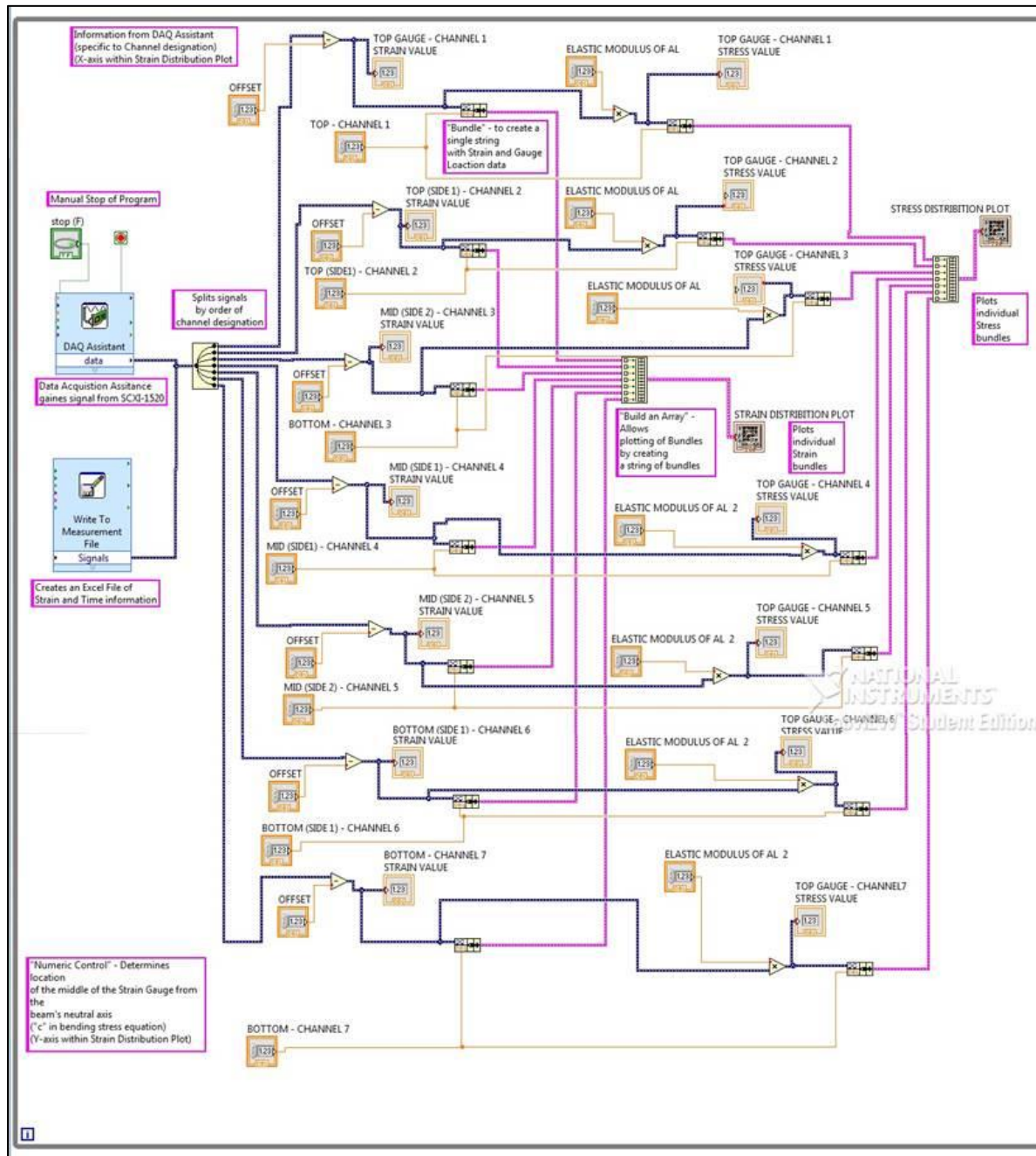


Figure 17. LabVIEW Program for Reading Bending Stress

Prior to testing, the values of strain gages need to be set to zero in the LabVIEW program in order to eliminate the offset values. The applied force can be calculated by using value of aluminum's yield stress,  $40,000 \text{ psi}^{11}$ , as maximum stress in the bending stress equation

(Equation 1). Then the maximum theoretical load value is yielded 10393 lb. The aluminum specimen, assembled in a pure bending configuration, is placed in the Tinius Olsen material testing machine to undergo the approximately 9000 lb. load. Once the load is applied, the data from the strain gages is transferred to the LabVIEW program, where the data is viewed in real-time strain and stress graphs as well as stored within a TDMS file compatible with Microsoft Excel. It is a good idea to plot the entire set of data to visualize graphical changes during the test. Figure 18 shows the Front Panel of the LabVIEW program containing the graphs of strain and stress distributions in respect to the location of the strain gages.

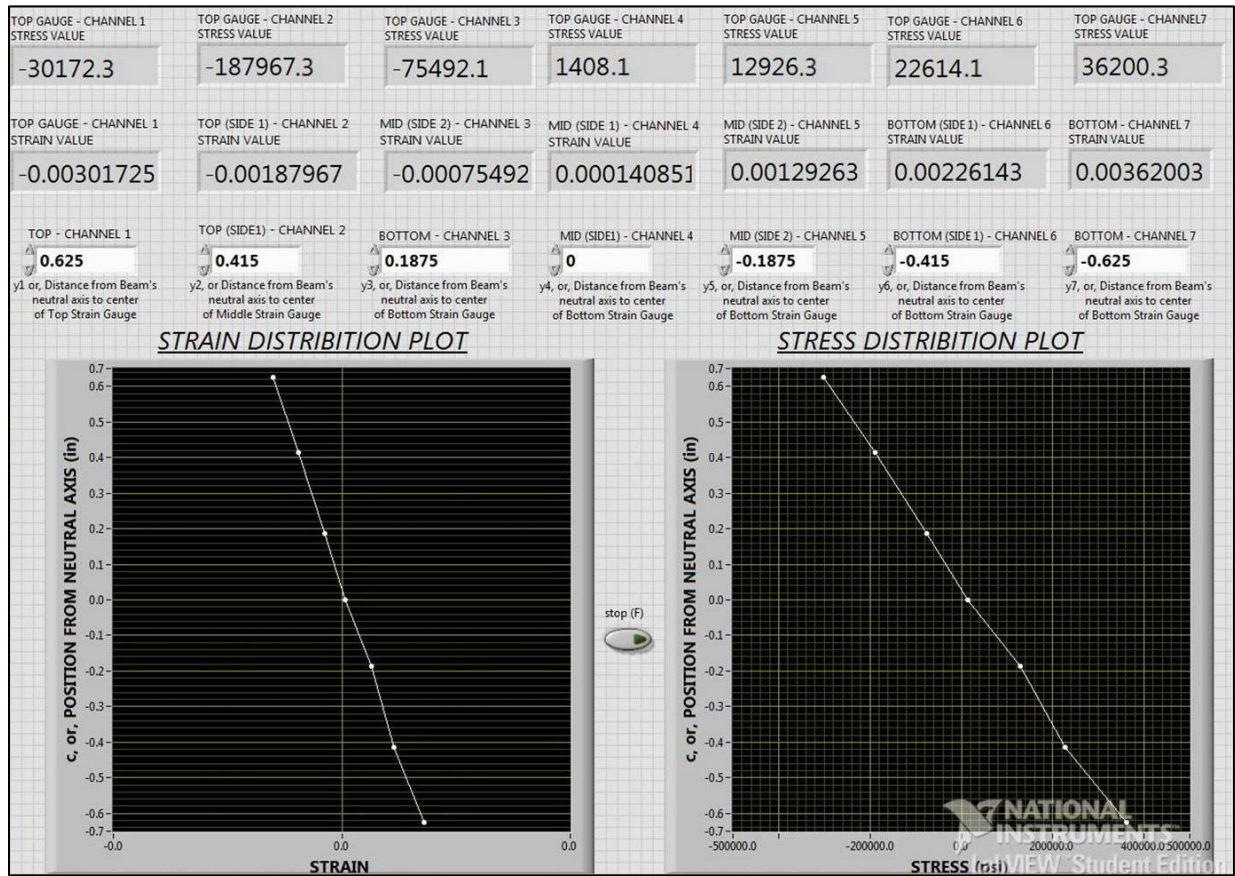


Figure 18. Front Panel with Strain and Stress Data

The experimental graphical curves and numerical values are compared with theoretical ones in order to validate the experiment. Comparing Figure 18, yielded from experimental values, with Figure 2, yielded from analytical method, reveals that they are similar in shape. Also, comparing the maximum experimental bending stress, 36,200.3 psi, with the maximum theoretical bending stress value, 34,494 psi, reveals only a 4.94% error, and proves that the LabVIEW program represents the mechanical properties of a specimen accurately.

#### d. Testing the Aluminum Bar for Measuring Shear Stress

After successfully measuring bending stress, the other aluminum bar is utilized to measure the transverse shear strain. Figure 19 shows the pure bending set up for reading shear strain values.

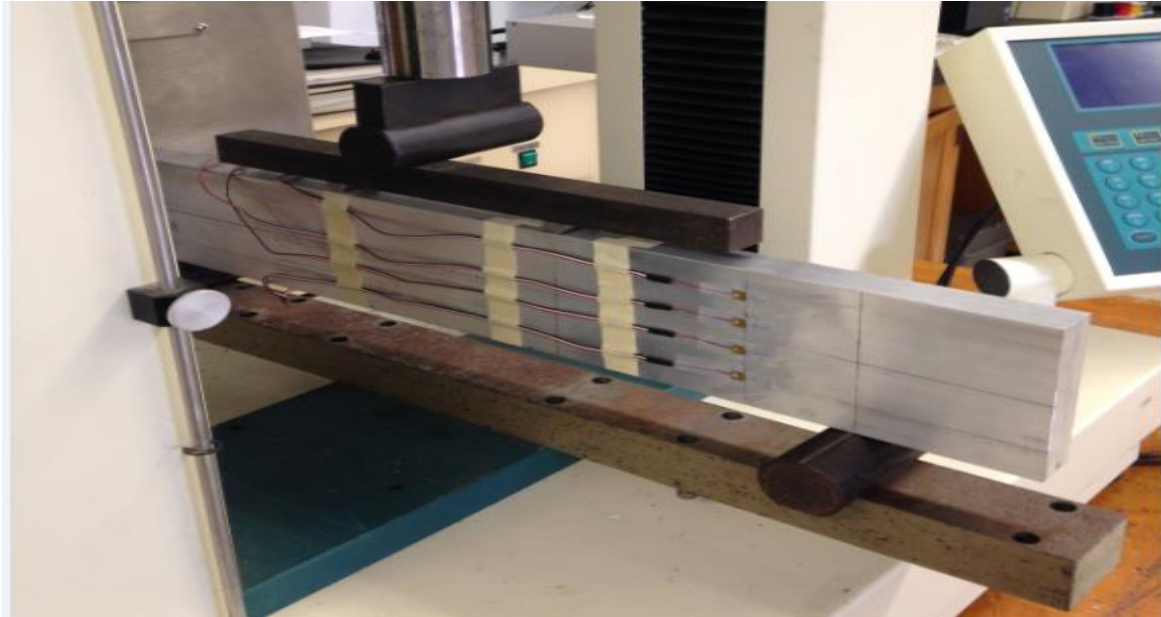


Figure 19. Pure Bending Set-Up for Measuring Shear Stress

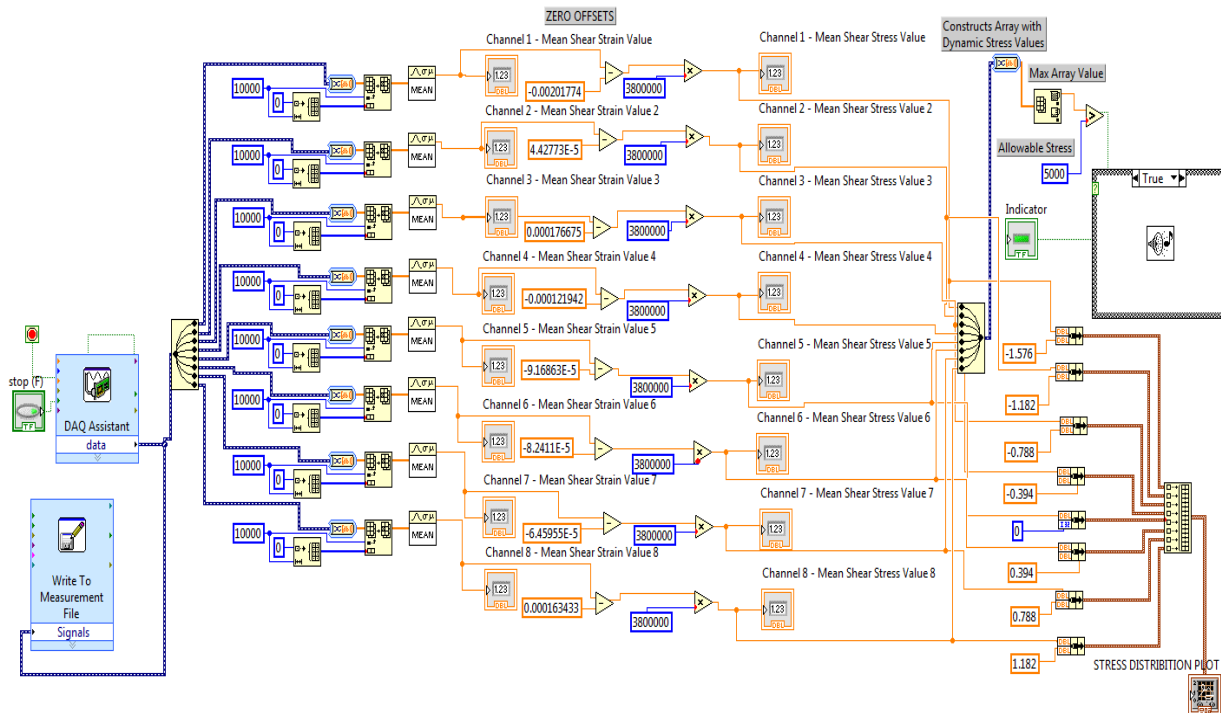


Figure 20. LabVIEW Program for Reading Shear Stress

The aluminum specimen is placed in testing machine to undergo an approximate 2920 lb. The load results in a maximum experimental shear stress value of 491.31 psi. Comparing the maximum experimental shear stress with the maximum theoretical value, 547.5 psi, reveals only a 10.2% error.

Figure 20 shows associated lab view software for reading shear strain. As indicated in figure 21, the program has an alert system to notify the user if the stress exceeds the allowable stress.

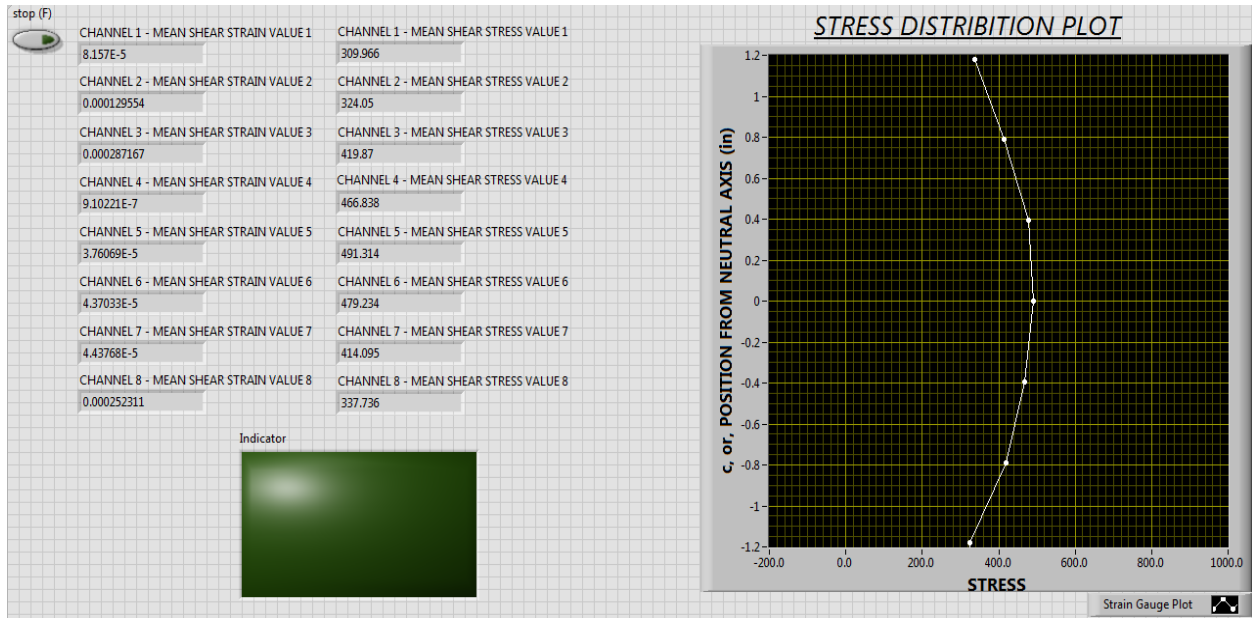


Figure 21. Front Panel for Shear Stress with Alarm

## Conclusion

The experimental stress and strain distribution curves, as well as numerical values, prove the ability to correctly read the data from the strain gages in the LabVIEW environment. Both measured and calculated results are presented and found to be in a good agreement. This project involved research, design, fabrication, constant testing, and extensive troubleshooting. The need of SHM within flight operations is a topic of great concern. Our project proved that sensors work on particular applications and they are safe and reliable to use for aircraft SHM. The experiment proved the ability to transfer data from mechanical properties of a part to a program and present the data in a readable, real-time graph. This technology, on a grander scale, could be utilized within the aircraft to gain information on critical components, and displayed within a simple format for the aircrew to reference during any air mission.

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