



## **Designing a Data Acquisition System for a Split Hopkinson Pressure Bar**

**Mr. Sean Patrick Kirby, University Of Maryland Eastern Shore**

Sean Kirby currently holds an engineering position with Pinnacle Solutions Inc. where he works as an IT Systems Engineer supporting NASA Wallops Flight Facility's Aircraft Office. Mr. Kirby received an Undergraduate Degree in Engineering with a Computer Engineering Specialization from the University of Maryland Eastern Shore (UMES) in December 2013. Prior to receiving his undergraduate degree, he served in the U.S. NAVY from 2002 to 2008 as Cryptologic Technician supporting both Operation Iraqi Freedom and Operation Enduring Freedom.

**Mr. Julius Omokiniowo Ejenavi, Morgan State University**

Julius Ejenavi Descriptive Bio: Julius Ejenavi is currently a full time graduate student at Morgan State University. Mr. Ejenavi is presently working on his Masters Degree in Electrical Engineering specializing in wireless communications. He received his Undergraduate Degree with Honors in Engineering with an Electrical Engineering Specialization from the University of Maryland Eastern Shore (UMES) in December 2013. In his Senior Design Project, Mr. Ejenavi worked in a team to design a Data Acquisition System for Split Hopkinson Pressure Bar (SHPB) Setup. At Morgan State University, Mr. Ejenavi worked on designing a 4-way coupler component that was inserted into the receiver front-end circuitry in a satellite communication link.

**Dr. Payam Matin, University of Maryland, Eastern Shore**

Dr. Payam Matin is currently an Associate Professor in the Department of Engineering and Aviation Sciences at the University of Maryland Eastern Shore (UMES), Princess Anne, Maryland. Dr. Matin has received his Ph.D. in Mechanical Engineering from Oakland University, Rochester, Michigan in May 2005. He has taught a number of courses in the areas of mechanical engineering and aerospace at UMES. He has served as departmental ABET committee chair through a successful accreditation visit in Fall 2012. Dr. Matin's research has been mostly in the areas of Computational Mechanics and Experimental Mechanics with applications in Solid Mechanics, Plasticity and Sheet Metal Forming. Dr. Matin has published more than 25 peer-reviewed journal and conference papers. Dr. Matin is the recipient of NSF MRI award as a Co-PI. Dr. Matin worked in Automotive industry for Chrysler Corporation from 2005 to 2007. He Joined UMES in August 2007. He is affiliated with ASME and ASEE professional societies.

## **Designing a Data Acquisition System for a Split Hopkinson Pressure Bar**

Senior students are always challenged to apply their engineering knowledge and research skills gained from an engineering curriculum toward design and implementation of challenging senior design projects. Split Hopkinson Pressure Bar (SHPB) is an apparatus that is used to study materials behavior under high speed deformation, where strain rate is very high. Hopkinson bars are usually custom made based on the needs of customers, who are mostly researchers in universities or research labs. In this work, in a form of a senior design project, the authors provided learning opportunities for engineering students to design a data acquisition system for a small size split Hopkinson pressure bar previously designed by former students. The objectives of this project are to engage a team of students 1) to design a data acquisition system using National Instrument hardware and Labview to collect strain data during high speed deformation testing 2) to design a data processing program to process the strain data collected to stress-strain graph 3) to conduct a number of high speed deformation material testing to validate the performance of the data acquisition system designed.

Students implemented the fundamentals of instrumentation, graphical programming, computational methods and solid mechanics to design the data acquisition system for a SHPB. A working prototype of the data acquisition system is integrated and tested. Preliminary tests demonstrate that the performance of the system is as desired. In this paper, the authors elaborate on how the students have utilized the engineering knowledge acquired throughout the course to design and develop the data acquisition system for the Hopkinson Split Pressure Bar and thus the educational gains achieved.

### **Introduction**

Material properties are the starting block for the design of most structures. Mechanical structures undergo a wide range of loading conditions. Structures can be loaded statically or dynamically with a wide range of strain rates. With impact loading with high strain rates, the relationships between stress and strain are not the same as when a material is subjected to static loading. It has been observed that material properties are dependent upon the rate at which it is deformed. Many investigators have studied the effect of high compressive strain rate loading conditions, in metals, wood, bones and other materials. The most common method for determining the dynamic response of materials is to use Split Hopkinson Pressure Bar (SHPB) [4].

The preliminary ideas behind Hopkinson Pressure Bar were first originated in 1872 by John Hopkinson [1]. Later, Bertram Hopkinson introduced a method to characterize the pressure variations with respect to time due to an impact produced by a bullet or explosive. Hopkinson was always capable of determining the maximum pressure and total duration of these impact events. However, the pressure-time curves were not accurate [1]. In 1941, Dennison Bancroft solved bar frequency equation for the velocities of longitudinal waves in cylindrical bars. The importance of Bancroft's work as applied towards Hopkinson bar testing was only realized much later when computers became integral tools for fast data processing. In 1949, Kolsky modified Hopkinson's original apparatus. The new apparatus was later named Split Hopkinson Pressure Bar (SHPB). In contrast to the original apparatus, Kolsky placed a specimen between two bars. He calculated specimen properties based on strain histories in the bars. The new two-bar

apparatus required measurements in both bars. Today, this two-bar technique has become widely-used testing procedure for high speed deformation.

Figure 1 shows the main components of a SHPB. The main four components are the Striker, Incident bar (Input bar), Transmitter bar (Output bar) and Specimen. The specimen is placed between the incident and transmitter bar. The striker acts as a projectile applying a high impact force on one end of the incident bar creating a compressive stress wave. The wave propagates in a uniaxial direction into the incident bar reaching the interface of the incident bar and specimen. A part of the wave reflects back as a tensile wave traveling in the incident bar while the rest continues to propagate into the transmitter bar as a stress wave.

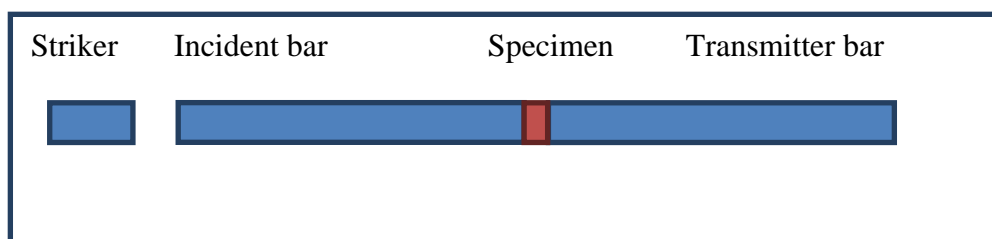


Figure 1- Schematic of Split Hopkinson Pressure Bar (SHPB) apparatus

The advanced structures such as military, aerospace and some energy-production structures may become subjected to high strain deformation such as impact. Thus, it is important to provide mechanical engineering students the opportunities to observe the dependency of stress-strain graph to strain rate. A low-cost small size SHPB serves this purpose very well.

In the previous work in the authors' institution, a team of undergraduate engineering students were engaged to utilize the fundamentals of mechanics along with Finite Element Simulation to design a small size low-cost SHPB for instructional purposes [9-10]. A working prototype of the setup designed was built. The performance of the prototype built was put into practice by a number of preliminary testing, data collection, and data interpretation. While the performance of the setup was promising, it was concluded that there should be a data acquisition system specifically designed for the setup.

The objectives of this project is to engage a team of students to 1) design a data acquisition system using National Instrument hardware and Labview to collect strain data during high speed deformation testing 2) design a data processing program to process the strain data collected to stress-strain graph 3) conduct a number of high speed deformation material testing to validate the performance of the data acquisition system designed.

While the project is a senior design project, it follows the following main educational goals:

- 1- The project aims to improve the ability of the student to design a realistic system and its components under realistic design requirements and constraints.
- 2- The project aims to improve the ability of the student to apply fundamental of mathematics, programming and engineering (such as solid mechanics, dynamics, instrumentation, numerical methods and testing and validation).
- 3- The project is to improve the ability of the student to apply modern engineering tools (such as Labview, Matlab and Excel) to analyze and design a realistic system and its components.

- 4- The project is to improve the students' hands on skills in fabricating a working prototype of the system.
- 5- The project aims to improve the ability of the student to design experiments, conduct experiments, collect data, analyze and interpret data.
- 6- The project aims to improve the students' written and oral communication skills.

The educational goals of the project correlate closely with most of the ABET student outcomes (a-k), which are widely accepted in engineering education community. These outcomes have introduced and mandated by ABET for engineering programs to ensure the quality of engineering graduates. Projects similar to this project would help engineering educators to cover many student outcomes in senior design classes, which improve the quality of engineering education. Two senior level students worked on this project over the course of two semesters under senior design project I and II classes. The students worked in the summer time between the two semesters. It is intended that the project complements the prior works of the other educators in improving senior design classes [5-8].

### **Nomenclature**

$P$  = Air Pressure

$L_c$  = Striker's cylinder length

$A_c$  = Cross sectional area of striker's cylinder

$m_{st}$  = Striker projectile mass

$L_s$  = Length of specimen

$A_s$  = Cross sectional area of specimen

$d_s$  = Diameter of specimen

$A_b$  = Cross sectional area of bars

$d_b$  = Diameter of bars

$t$  = Time

$C_0$  = Wave speed

$\dot{\epsilon}_s$  = Strain rate in specimen

$\epsilon_s(t)$  = Specimen strain history

$\sigma_s(t)$  = Specimen stress history

$\epsilon_R(t)$  = Reflected strain wave history measured on incident bar

$\epsilon_T(t)$  = Strain wave history measured on transmitter bar

$T$  = Time period

$f$  = Frequency

### **Apparatus Design Background**

In this section, a summary of the design and validation of the Split Hopkinson Pressure Bars apparatus is presented briefly. More elaborative details may be found in previous publications [9-10]. As shown in Figure 2, the setup designed included the following major components:

- *Compressor* is the pressure source that the striker projectile is provided in order to achieve the velocity and acceleration needed for an impact.
- *Pressure regulators* are used to decrease the pressure from the pressure source to a specified pressure for the system.

- *Striker Projectile* is a piece of metal inside a metal cylinder that uses the pressure provided to accelerate and achieve the velocity needed for an impact to the incident bar.
- *Pressure Valves* are used to work as a pressure switch to shut off or turn on the pressure into the striker cylinder.
- *Vacuum Pump* is used to apply vacuum in the striker cylinder in order to bring the projectile back to its initial position after an experiment is completed.
- *Incident and Transmitter Bars* are the two bars that sandwich the specimen in order to characterize the stress and strain that the specimen is undergone during testing.

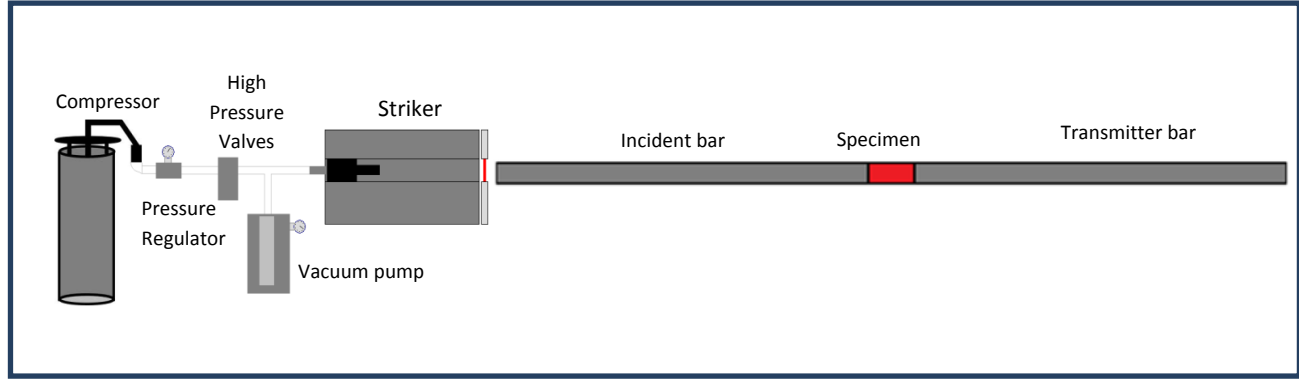


Figure 2- Schematic of Split Hopkinson Pressure Bar apparatus with pressure system

The Split Hopkinson Pressure Bar Apparatus was designed in the following 3 different design phases:

**Phase 1: Design of the incident and transmitter bars**

Considering a limited size for the setup as a constraint, the bars were designed with a large Length to Diameter Ratio to ensure uniaxial wave propagation throughout the bars. The length of the bars is chosen to be 0.75 m. The diameter of the bars is chosen as 19 mm. The bars are made of steel.

**Phase 2: Design for the pressure needed for the system**

The desired strain rate in the specimen was related to the velocity of the striker at the end of the striker cylinder. This velocity was calculated using the striker's acceleration. Newton's second law was implemented to estimate the striker's acceleration based on the pressure exerted on the surface of the striker. The pressure needed to generate the desired strain rate was formulized as follows [9]

$$P = \frac{\dot{\epsilon}_s^2 L_s^2 m_{st}}{2A_c L_c} \quad (1)$$

where  $P$  is the air pressure at the inlet,  $\dot{\epsilon}_s$  is the strain rate in the specimen,  $L_s$  is the specimen length,  $m_{st}$  is the striker projectile mass,  $A_c$  is the cross sectional area of the striker cylinder, and  $L_c$  is the length of the striker cylinder. Assuming known values for most of the variables on the left hand side of equation (1), the required pressure was estimated for any given strain rate.

Figure 3 depicts the graph of pressure  $P$  versus strain rate in the specimen  $\dot{\epsilon}_s$  for different lengths of the striker cylinder  $L_c$  plotted based on equation (1). This graph was used as a means to estimate the pressure required to generate any specific strain rate in the specimen. For a one foot striker cylinder, while a pressure of 75 psi was enough to generate the desired strain rate of  $5000 \text{ s}^{-1}$ , an air compressor with higher pressure capacity of 150 psi was selected for the setup.

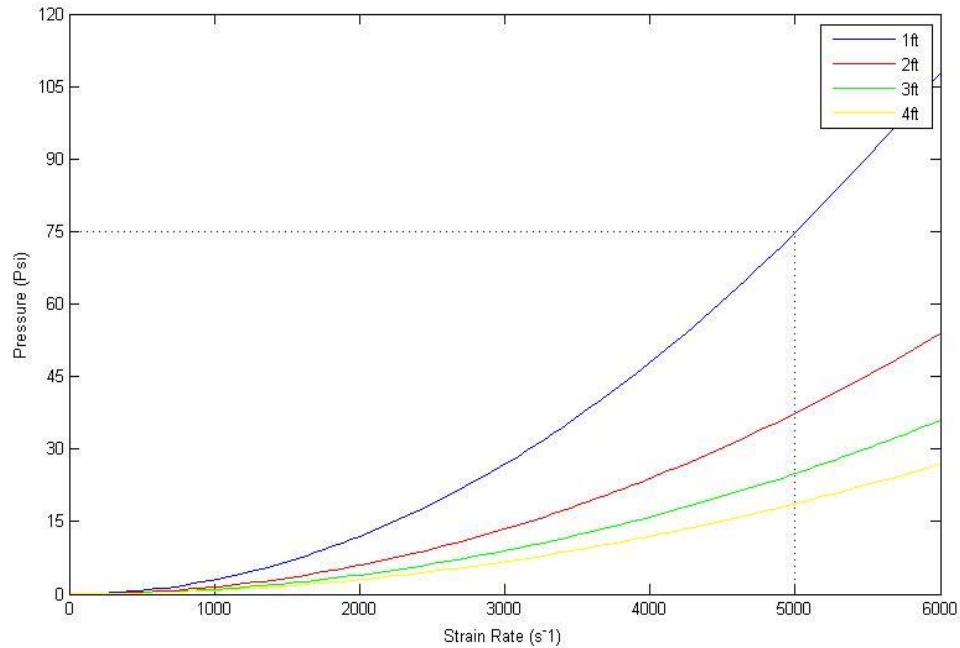


Figure 3- Pressure  $P$  (psi) versus strain rate in specimen  $\dot{\epsilon}_s$  ( $\text{s}^{-1}$ ) for different striker cylinder length  $L_c$  (ft)

### Phase 3: Design of the striker assembly

The length of the striker projectile  $L_{st}$  is selected in such a way that it does not cause any overlapping of wave signals in each bar. The length of the incident bar and the speed of the wave propagation in the bar are used to estimate the maximum possible length of the striker projectile.

Finite element simulation was conducted using ABAQUS to ensure that the striker cylinder sustains the maximum possible internal pressure that would be provided by the air compressor to accelerate the striker projectile. Finite element simulation was also utilized to verify the performance of the entire apparatus assembly during a high speed deformation testing. For this purpose, the dynamics impact between the striker and incident bar, and subsequent impacts with the specimen and the transmitter bar were simulated using finite element in ABAQUS [9-10].

The length of the striker cylinder  $L_c$  is selected as 0.3 m. The diameter of the striker cylinder was taken as 23 mm. The striker projectile was made of steel and weighed 0.2 kg.

After the design is verified and finalized, the solid model assembly of the apparatus was built using SolidWorks. Figure 4 shows the solid model of the final assembly of the designed Split Hopkinson Pressure Bar.

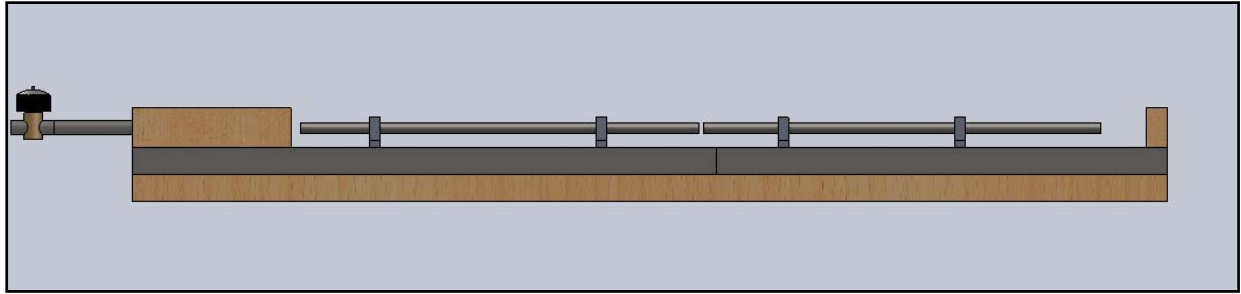


Figure 4- Solid model of the designed Split Hopkinson Pressure Bar (SHPB)

Figure 5 shows the designed SHPB attached to the compressor, which provides the air pressure necessary for high speed impact.

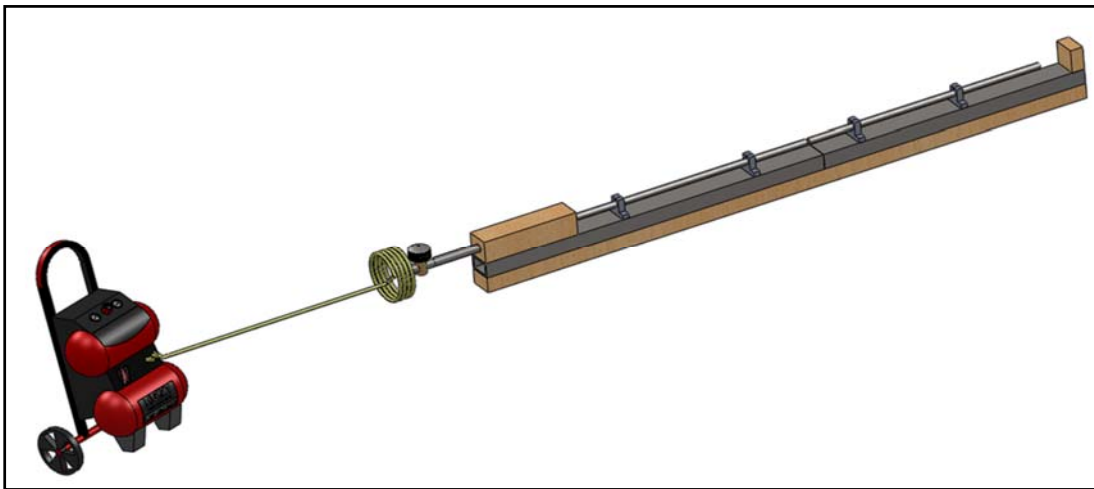


Figure 5- Solid model of the final assembly

After the design was finalized, the prototype was built. Figure 6 presents the prototype fabricated.



Figure 6- Split Hopkinson Pressure Bar (SHPB) prototype fabricated

### Problem Statement

The main purpose of this project is to engage a team of engineering students to design and prototype a data acquisition and analysis system that records the strain data collected by the strain gages on the SHPB, performs necessary calibrations, filtering and analysis of the data and outputs the stress-strain graph of the specimen. Ideally, the system should require a minimum of

user interaction or knowledge of the subject since it is intended for students with no previous experience in materials advanced testing.

The design needs are as follows:

- The acquisition portion of the system must collect synchronized data from both strain gauges on the incident bar and transmitter bar.
- The data collected must be in a format that can be imported to Microsoft Excel and MatLab for analysis.
- The collected data should have enough samples to allow a numerical analysis with reasonable accuracy.
- The stored data should then be analyzed to produce the stress-strain graph of the sample material.
- This process must be simple enough that a student with minimal prior knowledge of the experiment could perform the experiment independently.

The main design constraint is as follows:

For data collection, a National Instruments PXIe-1082 should be used since this setup would be the only device available in the institution that could input, process and store the data at the required sample rate.

### Theory:

During the SHPB testing, as the striker impacts the incident bar, the stress wave propagates all the way inside the incident bar until it reaches the specimen surface where some of the wave reflects back into the incident bar. The rest of the stress wave continues propagating through the transmitter bar. In classical SHPB analysis, the specimen strain and stress can be estimated using the strain signals measured on the incident and transmitter bars based on the equations derived in reference [11]. The specimen strain  $\varepsilon_s(t)$  is determined as a function of time by simply calculating the following integral.

$$\varepsilon_s(t) = \frac{-2C_0}{L_s} \int_0^t \varepsilon_R(t) dt \quad (2)$$

where  $\varepsilon_R(t)$  is the reflected incident bar strain history collected from the strain gauge mounted on the incident bar,  $L_s$  is the specimen length prior to impact, and  $C_0$  is the wave speed in the incident bar.

As long as the stresses in the bars remain under the elastic limit, the specimen stress may be calculated from the recorded strain history collected from the strain gauge mounted on the transmitter bar. Kolsky [2] developed the following relation to estimate the specimen stress  $\sigma_s(t)$  as a function of time.

$$\sigma_s(t) = E_b \left( \frac{A_b}{A_s} \right) \varepsilon_T(t) \quad (3)$$



where  $E_b$  is the bars' elastic modulus,  $A_b$  is the bars' cross sectional area,  $A_s$  is the sample's cross sectional area, and  $\varepsilon_T(t)$  is the transmitter bar strain history.  $A_b$  and  $A_s$  are calculated as

$$A_b = \frac{\pi d_b^2}{4} \quad (4)$$

$$A_s = \frac{\pi d_s^2}{4} \quad (5)$$

where  $d_b$  is the diameter of the bars and  $d_s$  is the diameter of the specimen.

In order to estimate the strain rate that the specimen experiences during the testing, equation (1) is re-arranged into equation (6). In this equation, the strain rate is derived in terms of the pressure as

$$\dot{\varepsilon} = \frac{1}{L_s} \sqrt{\frac{2PA_c L_c}{m_{st}}} \quad (6)$$

Graphing the specimen stress  $\sigma_s(t)$  estimated from equation (3) versus specimen strain  $\varepsilon_s(t)$  estimated from equation (2), the desired stress-strain graph is obtained for the specimen at the tested strain rate  $\dot{\varepsilon}_s$  estimated from equation (6).

### Data acquisition system design

The data acquisition system to be designed is divided into two sub-systems including data collection and data analysis. The data collection sub-system is responsible for collecting data using strain gauges mounted on SHPB setup. The data analysis sub-system is responsible for processing the data collected based on the theory presented to deliver the stress-strain graph of the material tested. Design tasks of each sub-system are assigned to each team member. The team members responsible for each sub-system meet regularly, and report to the faculty advisor weekly for design review. Figure 7 shows the schematic of the data acquisition system to be designed.

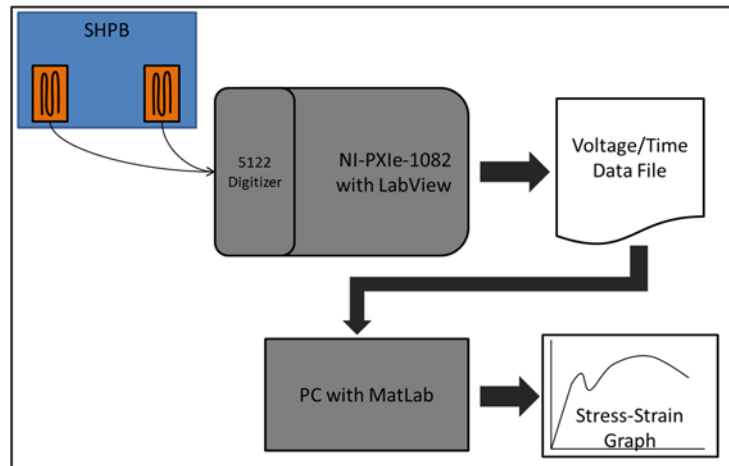


Figure 7- Schematic of data acquisition system for data collection and data analysis

As a main design constraint, the team members are required to use the PXIe- 1082 as an integral module of the data collection sub-system since this hardware is available in the institution through an NSF MRI grant. The National Instruments PXIe-1082 is a modular data acquisition and control system based on standard PC architecture with a high speed bus to allow for high frequency sampling and signal generation. It uses Microsoft Windows 7 and National Instruments LabView to control the operation of its eight expansion slots. LabView is implemented as graphical programming software for data collection on the PXIe-1082. The data analysis sub-system uses MatLab environment for the programming of the data analysis algorithms. MatLab has been chosen because it is widely supported within the institution and can be interacted with LabView.

### Design of data collection sub-system

Figure 8 shows the schematic of the data collection sub-system. The data collection sub-system is a link between the physical SHPB setup and the data analysis sub-system that determines the stress-strain characteristics of the sample material subsequently.

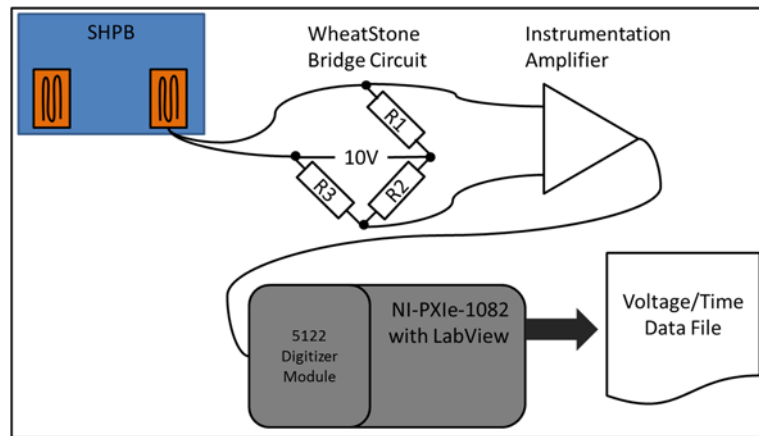


Figure 8- Schematic of data collection sub-system

The stress waves in the steel bars induce changes in the resistance of strain gauges. In the data collection sub-system, these changes in resistance are converted to proportional changes in voltage, and then amplified, digitally sampled and stored as numerical data. The data can be later visualized or processed as desired in the data analysis sub-system. In the following sections, the components of the data collection sub-system and the design choices made are covered.

### Sensing

3mm long 350  $\Omega$  strain gauges (model SGD-3/350-LY11) manufactured by Omega company are selected as sensing elements to be mounted on the incident and transmitter bars. The strain gauges chosen are easy to mount, not much sensitive to heat, and resistant to wear. They also allow for higher bridge voltage for transduction purposes. The 3mm gauges allow for an 8V bridge excitation voltage and can sense up to 30,000  $\mu\epsilon$  with a gauge factor (GF) of 2.0.

### Transduction

As a sensing element, the strain gauge only mimics the elongation of the material to which it is bonded. The change in resistance can only be detected by measuring a voltage change. Due to

low values of strains, the change in resistance is too small. If measured directly across a strain gauge, the voltage measurement would not be sensitive enough to reflect the resistance change in the strain gauge. The most common method to measure the resistance change through voltage measurement is to use a Wheatstone bridge circuit shown in Figure 9. A Wheatstone bridge is made of 4 resistors configured as shown in Figure 9. The bridge is powered up with an excitation voltage. In a balanced condition when all the resistors are the same, the output voltage is zero. That is also true if a balanced bridge contains a strain gauge in place of one of its resistors. In such bridge, the resistance of the other three resistors is selected as that of the strain gauge. Once the strain gauge experiences an elongation, its resistance changes and the bridge turns slightly unbalanced. In such situation, a non-zero output voltage is measured, which can be related to the resistance change in the strain gauge. Since two  $350\ \Omega$  strain gauges are selected for the SHPB setup, two  $350\ \Omega$  balanced Wheatstone bridges manufactured by Edtric Corporation on small printed circuit boards are selected that fits this application perfectly. An excitation voltage of 6.5V is considered for the Wheatstone bridges.

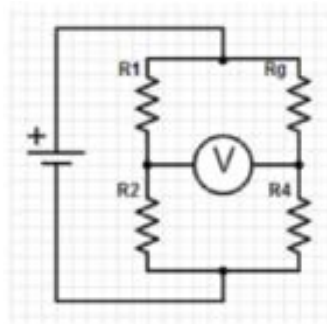


Figure 9- Schematic of Wheatstone bridge for transduction purposes

### Amplification

Because of the noise inherent in all digital sampling applications and the integral operation that must be performed during processing and data analysis, the voltage signal from the Wheatstone bridge must be amplified to collect an adequate signal. For this, an instrumentation amplifier circuit using the Texas Instruments INA126 is selected. This circuit board interfaces directly with the Wheatstone bridge excitation and output signal, which greatly simplifies the entire setup. The amplification gain is a function of the voltage used to power the circuit and the maximum input signal. The voltage that powers the amplifier is the same as the Wheatstone bridge excitation voltage of 6.5V. The maximum input signal is the maximum possible output voltage from the Wheatstone bridge. This signal is associated with the case where the maximum possible strain is measured by the strain gauge. This signal is calculated for a maximum strain of  $5000\ \mu\epsilon$ . Consequently, the amplification gain is calculated as 400 for the amplifier selected.

### Data acquisition module

The electrical components discussed are securely fixed into one enclosure named data acquisition module with minimal external wiring. Figures 10, 11 and 12 show the rear, front and top views of the data acquisition module.



Figure 10- Rear view of data acquisition module



Figure 11- Front view of data acquisition module

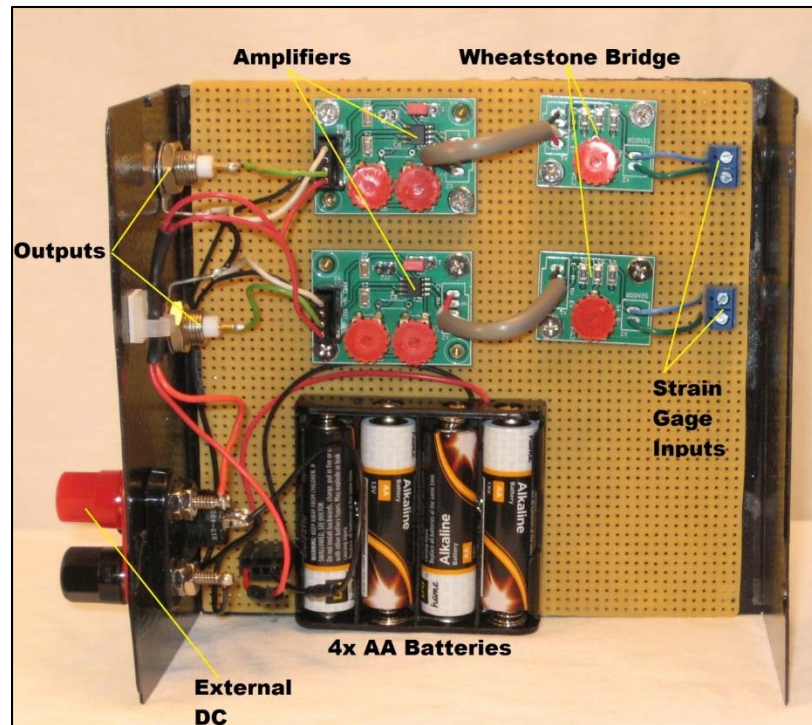


Figure 12- Top View of Data Acquisition Module

On the rear view, there are two channels labeled as CH0 and CH1, which receive the strain signals from the incident and transmitter bars. The strain signals pass through the Wheatstone bridges and amplifiers shown in Figure 12. The signals output from CH0 and CH1 ports as shown in Figure 11. As shown in Figure 12, the data acquisition module contains a screw terminal input, Wheatstone bridge, amplifier, and BNC output for each channel. The module is powered by a laboratory DC supply or four internal AA batteries. All the components are mounted on a panel of perfboard and placed in a recycled computer power supply case. Integrating the electrical components into such module minimizes electromagnetic interference and short circuit occurrence. The analog signals outputted from the data acquisition module input the NI PXIe-1082 for digital sampling.

### Digital sampling

To transform the analog voltage signals to digital data that can be stored and analyzed, a National Instruments PXIe-1082 with a NI-5122 expansion module shown in Figure 13 is used.

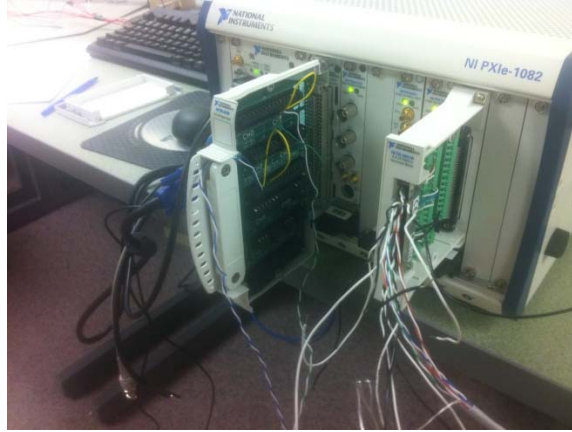


Figure 13- National Instrument PXIe-1082 data acquisition used for data collection

The PXIe and its expansion cards are controlled by National Instruments' graphical programming language, LabView. The 5122 module is a 14-bit, 100MS/s digitizer with 8MB of memory per channel. The digitizer also includes a standalone application called NI Scope that makes the entire system function as an oscilloscope. The voltage range and sensitivity of the PXIe is  $\pm 100V$  and  $\pm 2mV$ , respectively. These ranges are sufficient to detect the incoming signal without saturating the analog-to-digital converter. The required sample rate is determined using the average of pulse durations observed in the comparable sample data sets provided from the University of Rhode Island [12] at a strain rate of 7300/s. In their strain-time graphs, the first compressive wave on the incident bar lasted roughly  $100\mu s$  followed by a short period of inactivity, and a reflected wave lasted about  $100\mu s$ . This makes the total period of the strain wave  $200\mu s$ . The frequency  $f$  is then calculated as

$$f = \frac{1}{T} = \frac{1}{200 \times 10^{-6} \text{ sec}} = 10kHz \quad (7)$$

For every 100 samples desired within each cycle of the wave, the sample rate is calculated as

$$\text{Sample rate} = \frac{\text{Samples}}{\text{time}} = f \frac{\text{Samples}}{\text{cycle}} = \left( 10k \frac{\text{cycles}}{\text{sec}} \right) \times \left( 100 \frac{\text{Samples}}{\text{cycle}} \right) = 1 \frac{MS}{s} \quad (8)$$

The PXIe is capable of sampling well beyond this rate. That makes the limiting factor the available memory of the device and the amount of time that is available to perform the experiment at that sample rate. As stated previously, the available memory per channel is 8MB or

$$8MB = 8 \times 2^{20} \text{ Bytes} = 2^3 \times 2^{20} \times 2^3 \text{ bits} = 2^{26} \text{ bits} \quad (9)$$

Dividing the number of the bits available in the memory by the number of bits needed per sample yields the total number of samples that can be stored by the 5122 module during a single collection:

$$Samples = \frac{bits}{bits/Samples} = \frac{2^{26} bits}{14 bits/Sample} = 4,793,490 \text{ Samples} \quad (10)$$

This means that 4,793,490 data points can be held in the memory before an over floating error is generated by the PXIe and the program is halted. The sample rate selected defines the amount of the time available to perform an experiment before the memory is filled. For instance, for a sample rate of 1 MS/s, the maximum available time is calculated as

$$MaxTime = \frac{Samples}{Sample \text{ rate}} = \frac{Samples}{Samples/time} = \frac{4,793,490 Samples}{1 MS/s} = 4.79 \text{ sec} \quad (11)$$

For the higher sample rates, the maximum available time before the memory is filled is reduced. Table 1 provides maximum times available for recording data for different sample rates.

Sample Rate (MS/s)	Max. Time (s)
1	4.79
1.5	3.19
2	2.39
2.5	1.91
3	1.59
3.5	1.36

Table 1: Maximum recording time available for different sample rates

A sample program coming with LabView offers all the features needed to initialize the 5122 module for data collection. This program sets the desired sample rate and number of samples and stores the data into a text file and displays the data collected to an interactive graphing tool. A copy of this sample program is slightly modified to include graph labels and used as the data collection program for SHPB testing. The data collected can then be imported to data analysis sub-system for data processing and analysis.

### Design of data analysis sub-system

The purpose of the data analysis sub-system is to analyze the data collected from the SHPB testing to deliver the stress-strain graph of the material tested for the tested strain rate. The inputs to the program include the strain signals collected during SHPB testing from the incident bar and transmitter bar. Dimensions of the bars and specimen, material properties of the bar including modulus of elasticity, mass and the pressure of the striker are also constant inputs to the program. MatLab environment is utilized for the programming of the data analysis algorithms.

The strain signals collected during SHPB testing collected from the incident bar and transmitter bar are similar to what has been plotted in Figure 14. Once the strain signals collected are



inputted the MatLab program, the reflected strain signal  $\varepsilon_R(t)$  is identified from the strain wave of the incident bar. In the example depicted in Figure 14, the reflected strain signal has formed between 200  $\mu\text{sec}$  to 350  $\mu\text{sec}$ . The transmitted strain signal  $\varepsilon_T(t)$  is also identified from the strain wave of the transmitter bar for the same range as the reflected strain wave.

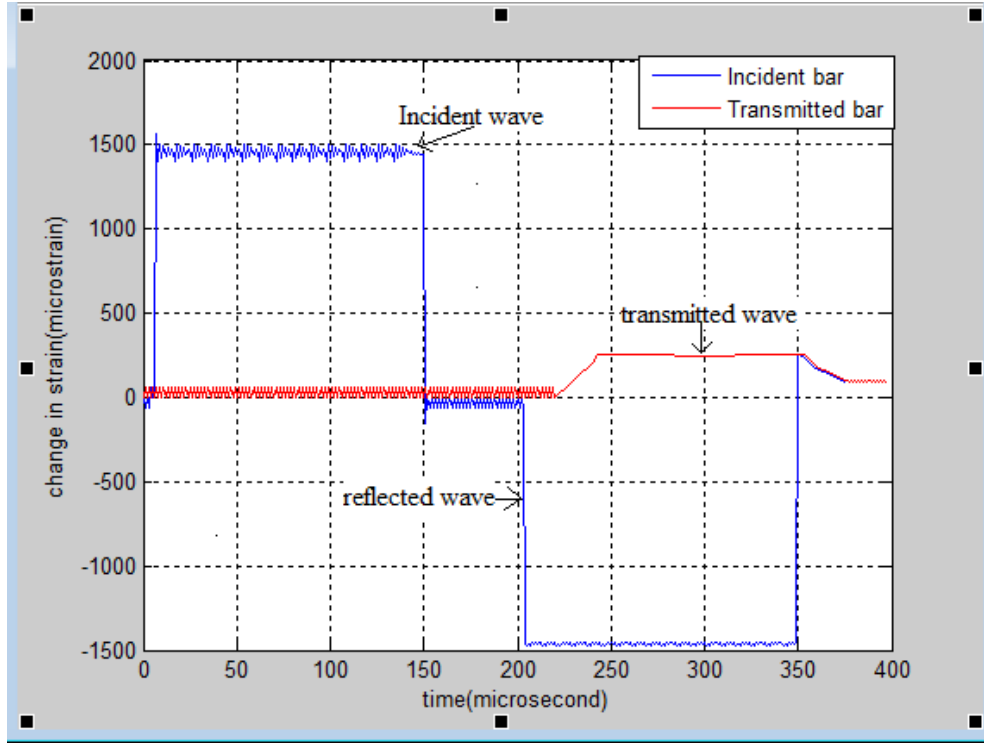


Figure 14- Reflected and transmitted signals identification

The specimen strain  $\varepsilon_s(t)$  is estimated based on equation (2) by calculating the integral of the reflected strain signal  $\varepsilon_R(t)$  identified earlier. This integral is calculated numerically through cumulative summation using cumtrapz built-in MatLab function [13], which works based on trapezoid method. The integration is carried out for any given data point of time within the range the reflected strain signal is identified. The specimen stress  $\sigma_s(t)$  is estimated based on equation (3) using the transmitted strain signal  $\varepsilon_T(t)$  identified earlier. The strain rate  $\dot{\varepsilon}_s$  that the specimen has experienced during testing is estimated based on equation (6) using the pressure  $P$  at which the test is conducted. Since both the specimen stress  $\sigma_s(t)$  and specimen strain  $\varepsilon_s(t)$  are stored for the same data points of time, the specimen stress-strain graph is obtained by plotting the specimen stress  $\sigma_s(t)$  versus the specimen strain  $\varepsilon_s(t)$  for the strain rate  $\dot{\varepsilon}_s$  calculated.

### Design validation of data analysis sub-system

In order to validate the MatLab program, a set of previously published raw data are collected on strain signals. These strain signals are inputted the MatLab program, processed and analyzed to deliver the stress-strain graph. The graph that the program delivers is compared against the published stress-strain graph given in the publication. The program is validated if these two graphs are in close correlation. The raw strain signals data presented earlier in Figure 14 has been taken from reference [14] for a H250 PVC foam specimen for the strain rate of  $2760\text{s}^{-1}$ .

The strain signals shown are inputted the Matlab program. Based on these raw data, the Matlab program calculates the specimen strain, and specimen stress as a function of time. Figure 15 depicts the specimen strain versus time. This figure indicates that the specimen experiences higher strains as time increases. A linear trend is observed for specimen strain versus time.

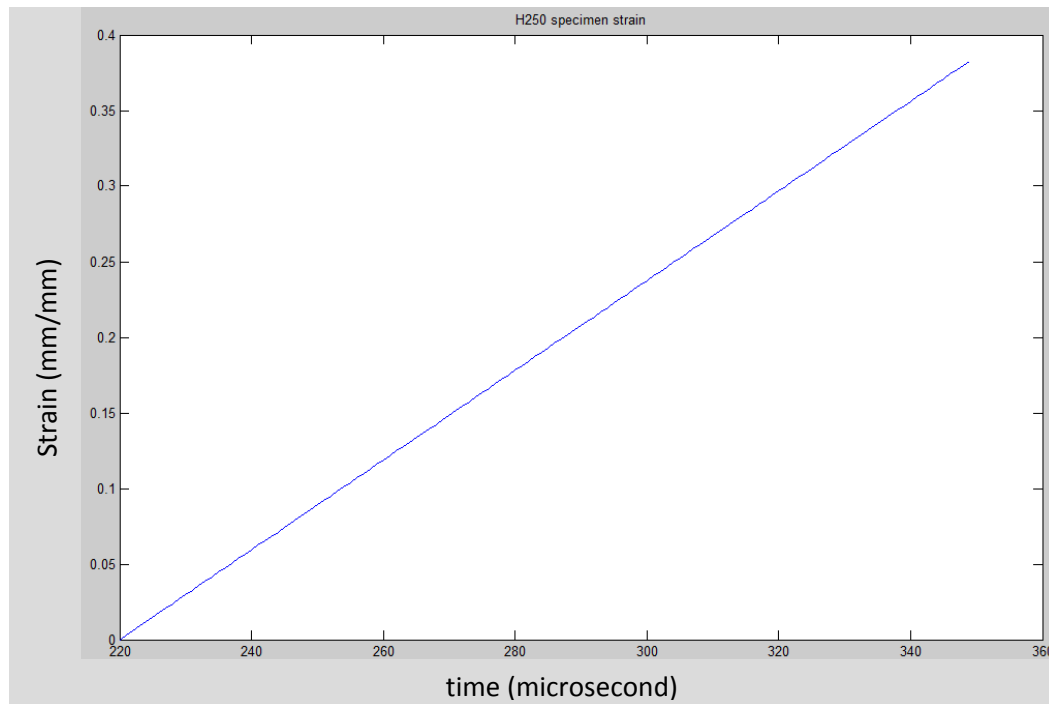


Figure 15- Specimen strain versus time obtained from the MatLab program for H250 foam.

Figure 16 depicts the specimen stress versus time. This figure indicates that the specimen stress increases linearly with respect to time up to some certain value (elastic limit). The specimen stress remains constant as the specimen passes beyond the elastic limit into the plastic deformation zone. Since the specimen stress and specimen strain are calculated and stored for the same data points of time, the stress-strain graph of the specimen is obtained by plotting the specimen stress versus the specimen strain as shown in Figure 17. As expected, the stress-strain graph exhibits a linear elastic region at the beginning of the deformation. As the deformation proceeds, the specimen experiences yielding and subsequent plastic deformation. The stress remains relatively in the same level as the specimen experiences higher strains in the plastic deformation zone.



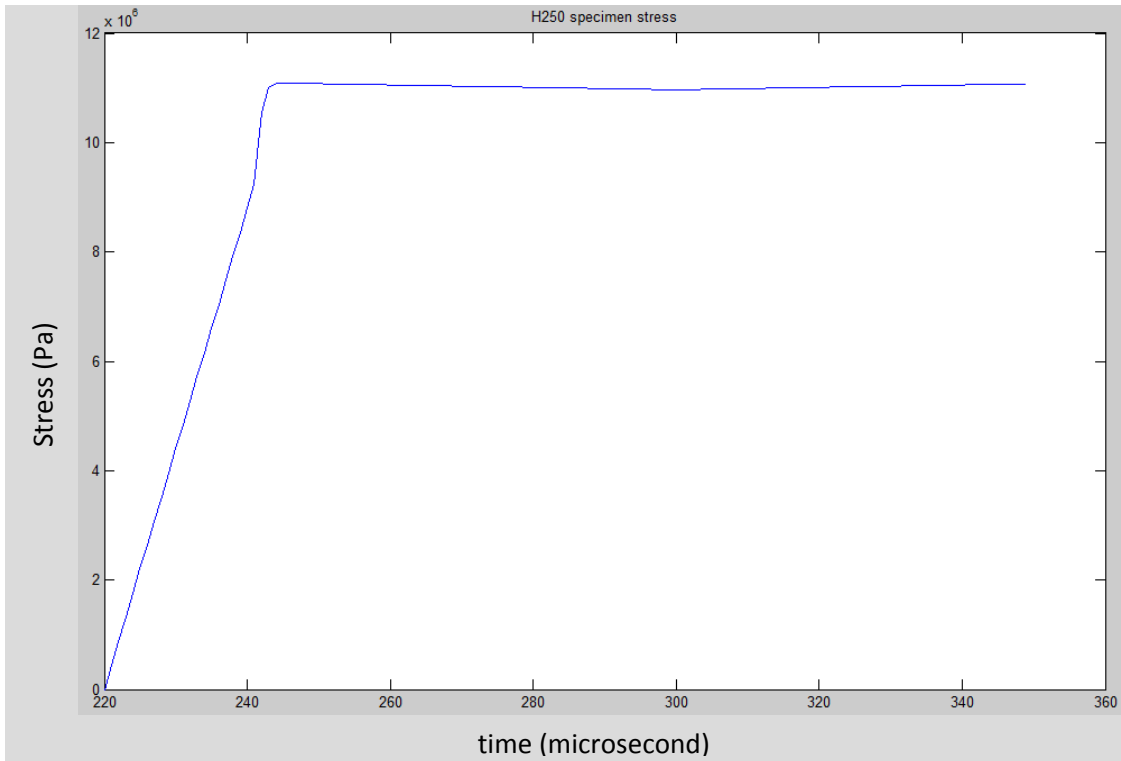


Figure 16- Specimen stress versus time obtained from the MatLab program for H250 foam

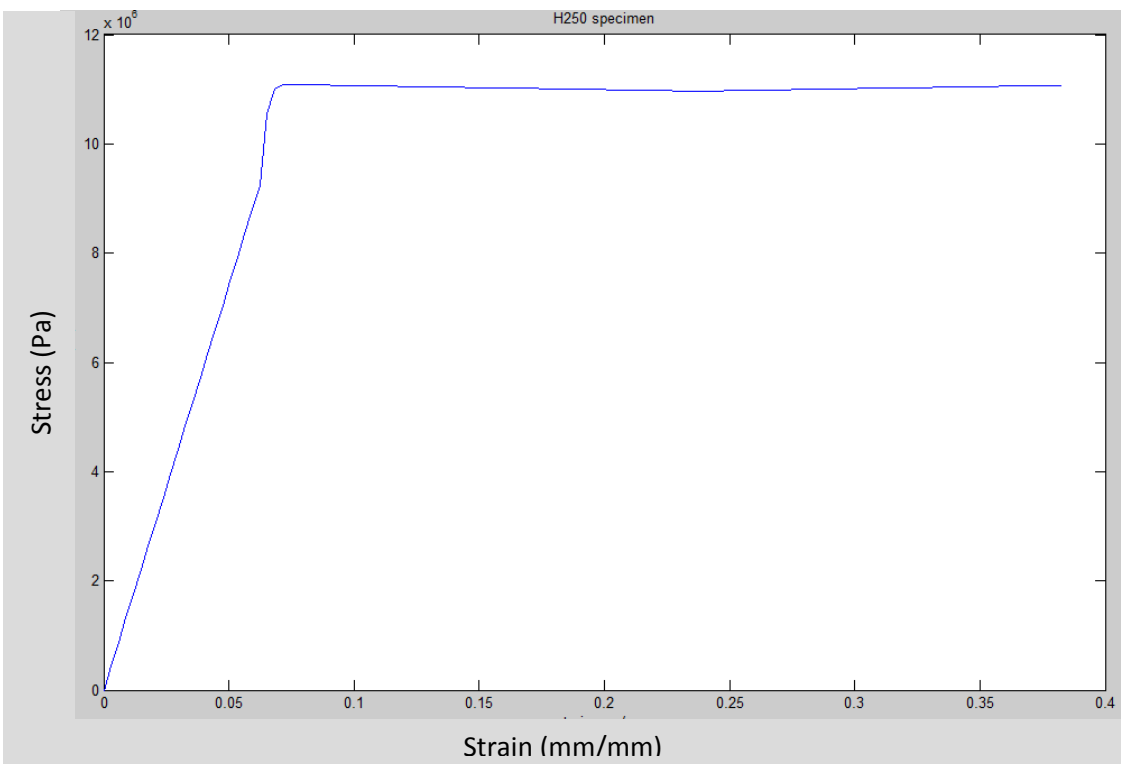


Figure 17- Calculated stress-strain graph of H250 foam obtained from MatLab program

The stress-strain graph (red graph) obtained from the MatLab program for H250 foam is plotted with the published stress-strain graph (blue graph) presented in [14] as shown in Figure 18. As depicted, there is a good correlation among these two graphs both in the elastic and plastic deformation zones. The agreement of the stress-strain graphs validates the performance of the MatLab program.

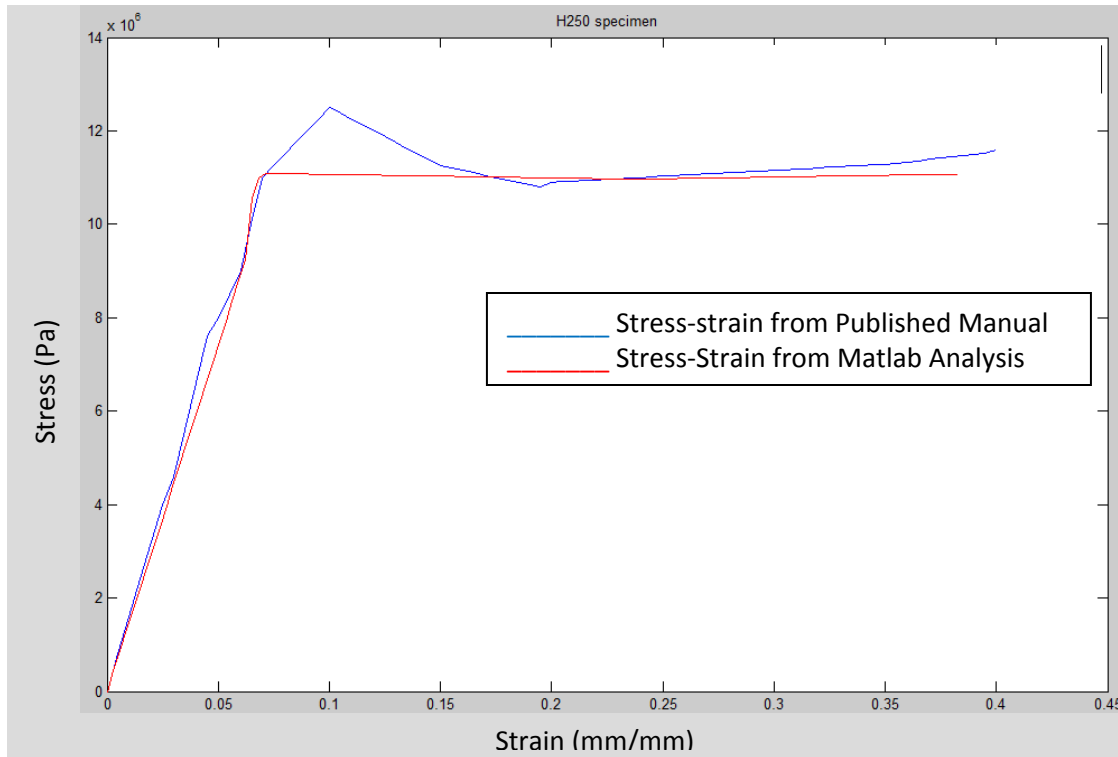


Figure 18- Predicted stress-strain graph (red) against published stress-strain graph (blue) for H250 foam

For more validation purposes, a second dataset is obtained from the University of Rhode Island (URI) Dynamic Photo mechanics Laboratory [12]. This package contained both the raw data from a SHPB test on an aluminum sample as well as the processed results of their analysis for comparison. The raw strain signals are inputted the MatLab analysis program. The program processes the data and delivers the stress-strain graph. Figure 19 depicts both the stress-strain graph obtained from the MatLab program (blue graph) and the stress-strain graph provided by the University of Rhode Island (red graph) for the same raw data. It should be noted that since the raw data provided is noisy and the MatLab program developed makes no attempt to filter or alter the signal, the stress-strain graph obtained features jagged appearance. Aside from the noise issue, it is observed that these two stress-strain graphs are nearly identical in different regions of deformation. Both the stress-strain graphs exhibit an elastic deformation zone at the start. After transition from yielding, the graphs feature an extended plastic deformation zone. The close agreement among these two graphs validates the performance of the MatLab analysis program.

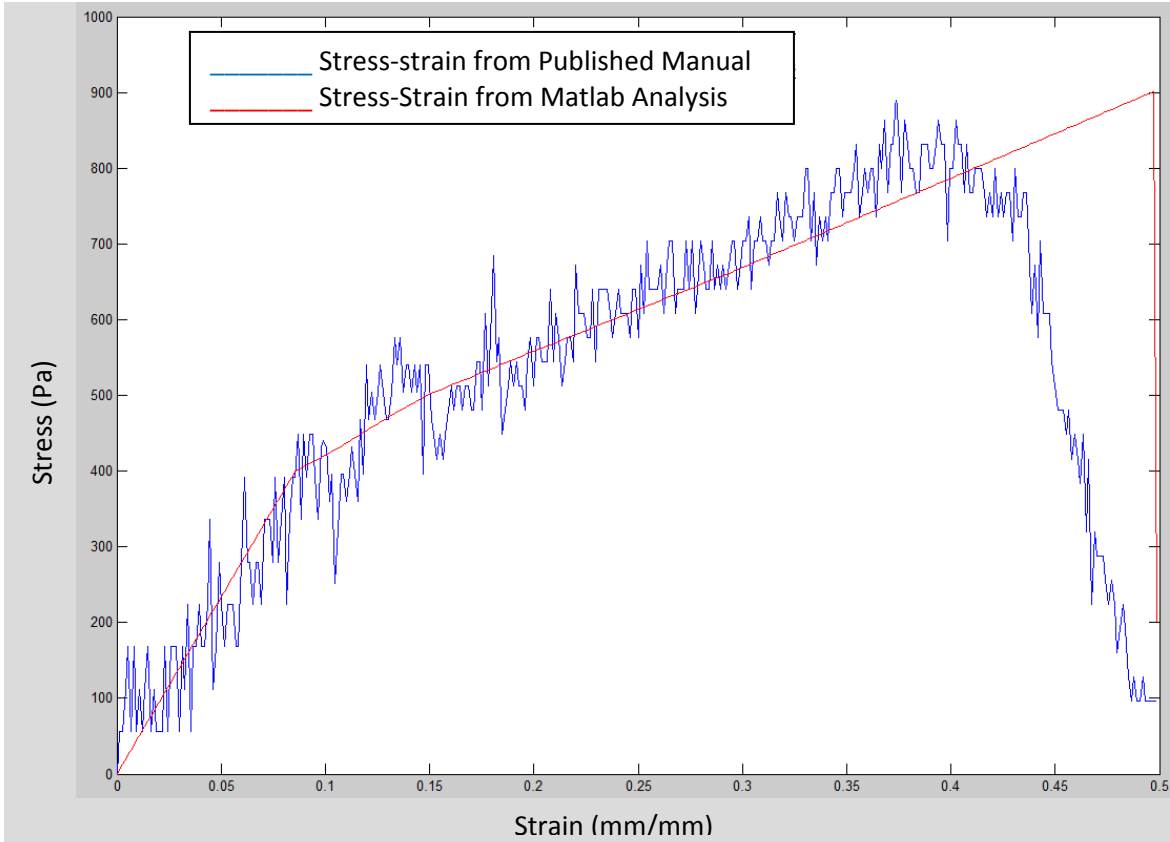


Figure 19- Predicted stress-strain graph (blue) versus that provided by URI (red)

### Testing and validation of entire data acquisition system

After data collection sub-system and data analysis sub-system are developed and integrated into the data acquisition system, the performance of the entire system needs to be examined. Under such examination, the performance of NI PXIe1082, acquisition module, LabView program, and MatLab program is validated collectively as a system. Cylindrical samples of Balsa wood are cut from a 1/4" diameter dowel. Balsa wood is readily available, inexpensive, easy to cut to required lengths and most importantly, there are some relatively comparable published results in literature [14] for comparison purposes. The values listed in Table 2 are considered for the SHPB experiment for validation purposes.

Sample material	Balsa Wood
Sample diameter $d_s$	0.00635 m
Sample cross-sectional area $A_s$	0.00003167 m <sup>2</sup>
Sample length $L_s$	0.01 m
Pressure $P$	50 psi
Strain rate $\dot{\epsilon}_s$	1443 s <sup>-1</sup>
Sample rate	2.5 MS/s

Table 2: Values considered for SHPB testing for validation purposes

The SHPB testing is conducted based on the procedure explained in [10]. The experimental data are collected in the form of strain signals and recorded successfully by the data collection sub-system. The data collected are visualized in the data analysis sub-system as shown in Figure 20. The strain signals collected contain the strain wave collected from the incident bar (blue graph), and the strain wave collected from the transmitted bar (green graph). The incident strain signal includes the reflected strain signal as well. The strain waves collected shown in Figure 20 are visually consistent with those observed in other SHPB experiments. However due to the inaccessibility to the raw data of the published results on Balsa wood, a direct comparison is not possible.

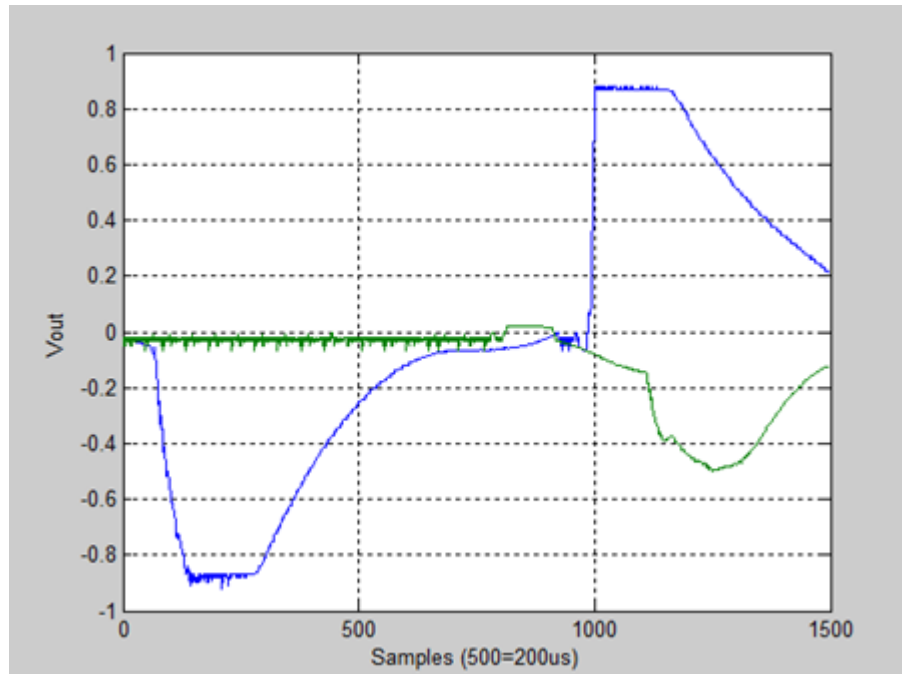


Figure 20- Strain signals collected and recorded by data acquisition system designed  
 Strain signal collected from incident bar (blue graph)  
 Strain signal collected from transmitter bar (green graph)

The data recorded is processed and analyzed in the data analysis sub-system. The stress-strain graph associated with the raw data collected is determined by the Matlab program. As shown in Figure 21, the stress-strain graph determined is plotted with the other stress-strain graphs available in literature [14] for the same material. The trend of the stress-strain graph calculated is as expected. The graph obtained features a linear elastic zone followed by yielding phenomenon, a transient deformation zone subsequent to yielding, and a nonlinear plastic deformation zone, which ends at a failure. The slope of the elastic line, which represents the modulus of elasticity, is comparable to the other graphs available in literature. The strain ranges in both the elastic and plastic deformation zone are comparable with the other graphs. The graph obtained seems to exhibit a noticeable error in terms of stress level around the yielding and subsequent transient region, but show less error in the plastics deformation zone. For the pressure used, the calculated strain rate for this experiment is  $1425\text{s}^{-1}$ , which is midway between the other top two published curves presented in Figure 21. That could partially explain the error observed while the other

factors such as calibration, range selection for the reflected wave and etc could also contribute in the error. More experimental efforts and potential modifications should be carried out to improve the results.

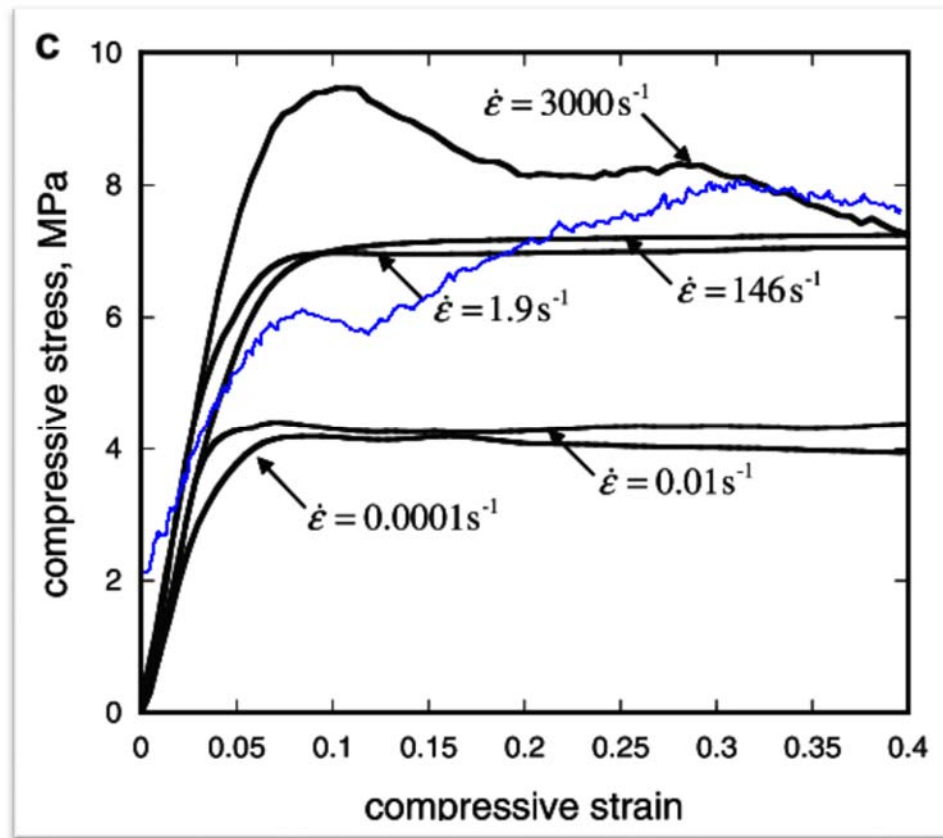


Figure 21- Stress-strain graph determined at strain rate  $\dot{\epsilon}_s$  of  $1425 \text{ s}^{-1}$  against stress-strain graphs available in literature [14] for Balsa wood

### Student Learning Outcomes

- 1- The project exposed two students to design process of a real world data acquisition system for SHPB system with realistic design requirements and design constraints.
- 2- The students developed a design approach to design the main sub-systems of the data acquisition system for the SHPB system.
- 3- The students learned how to apply the fundamentals of mechanics to calculate strain, stress and strain rate that a specimen experiences during high speed material testing.
- 4- The students learned how to select and work with strain gauges for sensing, Wheatstone bridges for signal transduction, and amplifiers for signal amplification.
- 5- The students gained valuable hands-on experience on how to implement National Instrument PXIe-1082 data acquisition system and Labview software in the SHPB setup for data collection and data recording.

- 6- The students gained hands-on experience working with MATLAB as a modern computational tool to develop a data processing and analysis program that complements the data collection.
- 7- The students learned how to operate a SHPB setup for high speed deformation material testing.
- 8- The students had a chance to successfully conduct a number of SHPB testing to validate the performance of the data collection and data analysis sub-systems.
- 9- The students took advantages of the prior results available in the literature to validate the performance of the system designed.
- 10- The students improved their oral communication skills by making weekly presentation to the audience of the senior design class and a faculty advisor.
- 11- The students improved their written communication skills by documenting the design, design verification, prototype fabrication, testing and validation.
- 12- The students had a chance to improve their project management skills by setting up project plan, time line and etc.
- 13- The students had a chance to work in a team framework and experience the challenges associated with it.

Faculty involved in this project received very positive feedback from the student who conducted the project. At the beginning of the project, the students thought that the topic was uncommon and unconventional. However, the students became interested in the topic as they read and learned more about the project. They were convinced that they had the opportunity to work on a design project, which involved them in applying math and engineering fundamentals toward the design of a data acquisition system. The students were satisfied that they gained practical experience with modern engineering tools and software. They were excited about the opportunity that they had to develop a system, and test the performance of the system. The students noticed that their oral and written communication skills have improved remarkably as a result of this project. The students viewed the project as a challenge since many tasks needed to be completed in a short period of time. The student realized that while the course materials are very helpful, they are not enough to conduct real world projects. To this end, they learned a great deal of extracurricular materials to successfully complete the project.

## **Future Work**

While exact duplication of the project may not be suitable for future senior design projects, the following suggestions may be considered to change the project for future similar projects:

- 1- The physical setup can be improved in terms of maximum strain rate capacity, size, complexity of striker, friction management, and etc.
- 2- The current setup has been designed for compressive waves. Similar projects may be defined for tensile mode or even torsional mode of deformation.
- 3- Some of the design requirements and design constraints may change. For instance, the constraint of using NI PXIe-1082 may be removed, and the students can be asked to design and developed their own standalone data collection system specifically for SHPB setup.
- 4- In the current system, after the experimental data are collected, there are some minor user interactions to initiate the data analysis process, which can be automated in future.

## Conclusion

Fundamentals of instrumentation and basic electronics have been used to design and prototype a data acquisition module that works with commercial NI PXIe-1082 data acquisition system for data collection from a student-designed Split Hopkinson Pressure Bar (SHPB) setup. Solid mechanics and dynamics fundamentals along with numerical methods have been utilized to develop a Matlab program to process and analyze the data collected from SHPB. The performance of the data analysis program has been validated using the existing data in the literature. A number of testing has been conducted to validate the performance of the data acquisition system designed. Valuable levels of knowledge have been gained through this undergraduate design/research project in the areas of solid mechanics, instrumentation, computational methods, programming, design, fabrication, testing and validation.

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