Quasi-Static and Dynamic Testing of Composite Materials

A Major Qualifying Project Report
Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE
in Partial Fulfillment of the Requirements for the
Degree of Bachelor of Science
in Aerospace Engineering

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ABSTRACT

The goal of this project was to create experimental tools and techniques to introduce the undergraduate students at WPI to the practice of material tensile testing. This primary goal would be achieved through the two concurrent sub-projects: 1) Development of tensile testing apparatus for quasi-static testing and 2) Development of Split Hopkinson Pressure bar setup for dynamic testing.

In the first sub-project, the team designed, analyzed and fabricated a 2000 pound-force tensile tester for the tensile testing of carbon fiber reinforced polymer composite specimens for students in the class 4717 Fundamentals of Composite Materials. This design and construction was guided not just by the various technical constraints but also budgetary and space constraints. The team conducted research and trade studies to select appropriate measurement and actuation components. The design team chose to utilize the Progressive Automations PA-17 linear actuator due to its simplicity of operation, professional quality, and warranty. Professional tensile testing grips with grip faces designed for composite material tensile testing, the 5K-WC-30 wedge grips, were purchased used from Force Test Inc. For load measurement, the Omega LC101-2.5K load cell was purchased. It was chosen for its availability, affordable price, force range (2500 pound-force), and acceptable accuracy for the project needs (0.1%). For strain measurement, VIC-2D digital image correlation (DIC) software was utilized. DIC strain measurement has become an industry standard, and allowing undergraduate students to gain experience with this software aligns with the project's purpose of providing students with real-world tensile testing experience. After test column components were chosen, the main supporting structure was designed. Initially, calculations were done by hand to determine basic design parameters of the support structure. Designs were then created in SolidWorks software. The static and buckling simulation tools in SolidWorks were used to perform a theoretical structural analysis. Designs were then discussed with advisors and industry professionals to optimize cost, ease of machining, and ease of use. The final support structure utilizes two posts, a bottom mounted actuator to create a natural working height, and thick steel top and bottom plates to reduce the compliance of the frame. Structural components were machined in WPI's Washburn Labs. After all structural components were fabricated, the testing machine was assembled in WPI's Higgins Labs.

The tensile tester would be controlled by desktop computer using a LabVIEW script and NI DAQ provide a pulse width modulation (PWM) signal to a Victor motor controller, which adjusts the output of the actuator. The physical limits of the actuator ensure that the machine does not exceed its operating limits. The total cost of the tensile testing apparatus was $2,922.27. This is a significant cost reduction from commercial tensile testing machines. This low cost was achieved through the use of low-cost non-structural components, and in-house fabrication of structural components.

In the second sub-project, the team redesigned and reconstructed an existing incomplete, Split Hopkinson Pressure Bar (SHPB) apparatus to accurately and precisely measure dynamic response in composite materials. The SHPB is a common system for measuring this type of mechanical response in the Aerospace Engineering industry. Utilizing one-dimensional wave propagation theory, the SHPB is able to measure the dynamic stress and strain responses of a material with only its physical dimensions known. This particular SHPB was designed and constructed as part of a 2017 MQP and consists of a single-stage gas gun, a striker bar projectile, two pairs of incident and transmission bars made from Maraging 350 steel and 7075-T651 aluminum respectively, a momentum trap, two half-bridge strain gage circuits with amplification, and an oscilloscope. The SHPB system operates by launching the striker linearly from the gas gun, where it makes contact with the incident bar. A compressive strain wave propagates along the incident bar until it reaches the test specimen. When the compressive strain wave contacts the specimen, some of the wave is reflected back along the incident bar, some of the wave is absorbed by the test specimen, and some of the wave is transmitted along the transmission bar. The strain gages mounted on the incident and transmission bars measure the incident, transmitted, and reflected strain waves. This data is recorded on the Tektronix MDO 3024 Oscilloscope at high sample rates (up to 200 million samples per second). The data collected by the oscilloscope is then filtered for noise and processed to calculate the dynamic strain and true stress response using MATLAB.

ACKNOWLEDGMENTS

The project team would like to show our sincere appreciation for the people who made this project possible. Thanks to the WPI Mechanical Engineering Department and Aerospace Engineering Program for providing generous funding for the project. Thanks especially to Professor Nikolaos A. Gatsonis - Aerospace Program Director and Professor Jamal Yagoobi - Mechanical Department Head. The project team would like to thank the Washburn Shops Instructional Laboratory Technicians and Ian Anderson in particular for their assistance in machining parts of the apparatus. Thanks to David Bee from Force-Test who went above and beyond in helping us understand details about the grips and construction of tensile testers in general. A sincere thanks to Dr. Anthony B. Linn who consulted on the project; his engineering experience was absolutely critical to our design efforts. Thank you to Sharada Bhavanam for her help with all the small and irritating details. And of course, thank you to our advisor, Professor Nikhil Karanjgaokar for guiding us every step of the way.

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1. QUASI-STATIC TENSILE TESTER FOR COMPOSITE MATERIALS

1.1. Introduction

The WPI Aerospace Engineering program has recently restructured its course offerings to include a composites class at the undergraduate level. This course, AE4717 - Fundamentals of Composite Materials, teaches students about the fabrication and behaviors of various composite materials relevant to the aerospace industry.

As part of the WPI educational philosophy, project-based learning is an important part of the educational experience. Therefore students enrolled in AE4717 will fabricate and test their own samples of carbon fiber reinforced polymer (CFRP). However, the program does not possess a testing apparatus that can perform tensile and fatigue testing on composite samples. Most testing machines available for purchase would be prohibitively expensive.

1.1.A. Project Statement

The purpose of this project is to design and deliver a machine to conduct tensile tests on composite materials within a budget of 3000 dollars. This testing apparatus should be able to perform tensile testing on a sample of CFRP fabricated by undergraduate students.

If possible within budgetary constraints, it is also strongly desired that the machine be capable of running fatigue tests on the same material.

Figure 1. A commercial tensile tester [1].

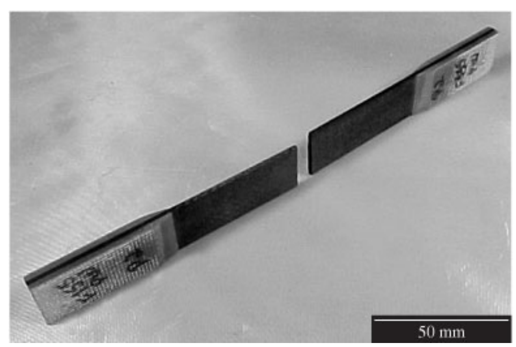


Figure 2. Composite specimen tested to failure. [2]

To achieve this goal, the following objectives were identified:

- Pull in tension with a force of 10kN
- Hold a sample of CFRP against that 10kN

- Survive light use for a minimum of 10 years, while having the potential to be upgraded with different actuators/load cells
- Provide testing data that is accurate enough to sufficiently determine properties of the material being tested
- Have automated testing modes for both tensile and fatigue testing

1.1.B. Summary

The purpose of this project is to design and deliver a tensile tester to be used in the new course, AE4717 - Fundamentals of Composite Materials. The apparatus should be able to test CFRP to failure, and fatigue to failure if possible. The testing apparatus must be designed and fabricated within a budget of 3000 dollars provided by the WPI Aerospace Engineering Program and the WPI Mechanical Engineering Department. The remainder of this paper will discuss the design process in detail, what decisions were made and why, as well as what other paths could have been taken to achieve the objective.

1.2. Gap Analysis Tensile Testing

A gap analysis was performed to assess the value of the project and define a more appropriate solution than purchasing a preexisting testing apparatus. The following sections expand on this basic idea, and demonstrate the potential value provided by the project.

1.2.A. Desired System

The purpose of this project is to design and deliver a machine with the ability to conduct tensile tests on composite materials. The machine will be designed for lab use in an undergraduate composites class. It is further desired that the system be as inexpensive as possible while maintaining crucial design elements. At the initial design step, the funding group (WPI Aerospace Engineering Program and the WPI Mechanical Engineering Department) had not yet agreed on a budget for this project. The project team created multiple quotes for machines with different functionalities.

1.2.B. Existing Systems

There is not currently a system in place that fits the established requirements. WPI currently has some tensile testing machines, but all are unsuitable for various reasons. Many of the machines, such as the picomotor peel / tensile testing machine pictured in Figure 3 cannot provide the 10kN of force needed to adequately test a CFRP composite sample. Other tensile testing machines are simply too expensive to be used by undergraduate students taking a class. These machines are reserved for researchers who have extensive training in their use, and a legitimate need for the level of accuracy that these machines provide.

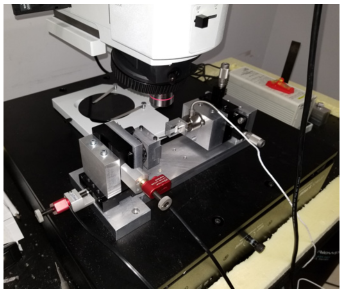


Figure 3. WPI picomotor peel/tensile tester

Figure 4. TestResources 140 Family Universal Test Machine [3]

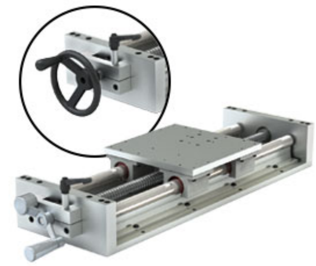


Figure 5. PCB Linear, 2HCR Linear Slide

Beyond the systems currently owned by the WPI Mechanical Engineering Department, there are some systems already in existence that could be purchased "off-the-shelf" that meet the requirements of this project. One such system is the TestResources 140 Family Universal Test Machine (pictured in Figure 4). It is fully customizable, and could easily be configured to meet the testing requirements established by the AE4717 labs. However, this system is unable to conduct fatigue testing. A customized quote shows that this system would cost on the order of $15,000, which greatly exceeds the project budget. It also has some unnecessary additional capabilities, such as compression, flexure, and peel testing capabilities that are not required for the system and add unnecessary cost.

1.3.C. Promising Technologies

As cost is a primary consideration, the promising technologies for this project tend to be simpler, tried and true solutions, rather than more novel items. For example, the bare minimum needed for a tensile test is a way to apply and measure stress and to measure strain. Tensile testers apply a load via some sort of actuator, most often electromechanical actuators, or stepper motors with lead screws. However, it is possible that we would load our samples using a hand crank and a very high gearing ratio. This would significantly reduce cost and complexity of the testing apparatus. The pictured professional-quality system from PBC Linear (Figure 5) costs about $3,000, however, a similar machine fabricated at WPI by the project team would be significantly cheaper.

1.4.D. Gaps

The gaps here are relatively straightforward. Systems already exist to perform the tests required by this project. The only significant gap is cost. However, that should not be dismissed, as we are looking to design a system on a budget of only a third of what these systems normally cost.

Summary Table

Current State	Desired Future State	Gap	Risk(s)	Development Plan	Comments
$15,000 for all-inclusive system	Tensile testing system within budget of $3,000	Price	Moderate; issues with custom manufacturing or inexpensive parts could lead to failure	Break system down into components and redesign and fabricate as inexpensive as allowable	In a complete redesign, some loss of functionality is expected and acceptable (such as compression)

1.3. Systems Engineering Considerations

This project is being documented using Systems Engineering principles. This section contains an explanation of these principles and methodologies.

1.3.A. Systems Engineering Methods Used

There are many Systems Engineering methodologies used in this paper. The first of these is a stakeholder and needs analysis. In this section, the stakeholders of the project are identified and prioritized. Then the needs of each stakeholder are determined and prioritized. This determination of not just what we need, but why we need it is critical to have a solid understanding of the project. Chapter 0 details another Systems Engineering Method, the Concept of Operations (CONOPS) which is carried out to visualize the system from an operator's perspective. Chapter 0, 1.4.B. High-Level Design makes use of more Systems Engineering methods, especially risk management, trade studies, and functional architecture.

In addition to the systems engineering activities included in this paper, the project was approached from a systems engineering mindset. Being certain to solve the right problem, and continuous communication with stakeholders was paramount. Particular attention was given to tractability, the Systems Engineering focus that design should be traced back to requirements, which can be traced back to needs, which can be traced back to stakeholders.

1.3.B. Stakeholder Analysis

Stakeholders for this system are summarized in Table 1.

Table 1. Key Stakeholders

Title	Description	Role	Priority
Professor Karanjgaokar	WPI Professor specializing in composite materials	Advisor *and* Customer	1
Graduate Teaching Assistant	Graduate Student who will help undergraduates operate the machine	User	1
Undergraduate Composites Students	Students who will use the machine as part of their class	Primary User	1
WPI Aerospace Engineering Program and WPI Mechanical Engineering Department	Primary customer; providing funds	Sponsoring Organization	2
ASTM	Standards Institution; describes standard tensile testing procedures	Provide Standards	2
Researchers	People in the WPI community who would use the machine to conduct composites research	Potential occasional user	3

Professor Karanjgaokar

Description/Role: Professor Nikhil Karanjgaokar will be the instructor for AE4717 - Fundamentals of Composite Materials. He also serves as the advisor of this project effort. Therefore, he is the source of a large amount of the information for needs of the system.

Basic Needs: The basic functionality needs of the system are traceable to Professor Karanjgaokar. This includes basic tensile testing and fatigue capabilities.

Graduate Teaching Assistant

Description/Role: For the course AE4717 – Fundamentals of Composite Materials, there will be a graduate teaching assistant (TA) who will manage the laboratory aspects of the class, and assist students is using the machinery. For the first offering of this course, that TA is Sharada Bhavanam.

Basic Needs: The graduate student cares particularly that the system is easy to use and maintain.

Undergraduate Composites Student

Description/Role: The students are the primary users of the machine and the people for whom the machine is primarily being developed. Professor Karanjgaokar is describing the student's needs.

Basic Needs: The students need a way to test the samples of carbon fiber reinforced polymer that they will fabricate. Beyond that, the students need the machine to be usable and give understandable output (with a little bit of help from the TA).

WPI Aerospace Engineering Program and WPI Mechanical Engineering Department

Description/Role: The Aerospace Engineering Program and Mechanical Engineering Department are the sponsoring organizations for this project. They will provide some amount of funding for the construction of the machine. They are represented by the Aerospace Program Director: Professor Nikolaos A. Gatsonis, and the Mechanical Department Head: Professor Jamal Yagoobi.

Basic Needs: The program needs the system to be as inexpensive as practical, so funds can be allocated to other projects. The program would also like the functionality of this machine to be extendable to other aerospace projects.

ASTM

Description/Role: ASTM is a standards institution that provides relevant standards for conducting tensile tests on composite materials. Adhering to this helps ensure that tests will give valid, repeatable results when compared with tests from other systems. Relevant ASTM standards are [4], [5],[6].

Basic Needs: Regulations for tensile testing of composite materials (primarily ASTM D3039) explain that there is not a true, broadly accepted standard for testing composite materials. Still, best practices include making use of standards when practical, and it is good to document when such use is not possible.

Researchers

Description/Role: It is possible that individuals conducting research within the WPI community would find it useful to use this device for performing tensile tests on their own materials. It is not a primary design goal to account for these potential users, but it is good to accommodate them if possible.

Basic Needs: Researchers would like the ability to test stronger/larger/thinner samples than the undergraduate students. They would also like the machine to have some level of upgradability so that a more precise motor or load cell could be used for a particular application.

1.3.C. Needs Analysis

Needs were gathered through discussion with available stakeholders: Professor Kanarjgaokar, Sharada Bhavanam (Graduate TA), and Professor Gatsonis (WPI Aerospace Program Director). Needs were also discovered through careful research, including research into ASTM standards. Needs are summarized in Table 2.

Table 2. System Needs

Title	Description	Trace to Stakeholder	Priority	Complexity
Rigidity	System should allow less than 0.01% compliance when stretching a sample	Professor Karanjgaokar, Undergraduate Composites Student	Medium	Medium
High Force	System should be able to apply a maximum force of 10 kN	Professor Karanjgaokar	Medium	Medium
Sample Size	System should be able to test samples of CFRP 1mm x 10mm x 5cm in size assuming a maximum deformation of 50%	Professor Karanjgaokar, Undergraduate Composites Student, ASTM D3039/D3039M – 14	Medium	Low
Hold Sample	System should be able to grip samples of CFRP with no slip when testing at up to 10kN	Professor Karanjgaokar, Undergraduate Composites Student	High	Medium
Accept large samples	System should be able to test samples up to 25cm in length	Researcher	Low	High

Resolution of applied force	Force should be able to be applied in variable increments to allow a minimum strain resolution of 1 µm	Professor Karanjgaokar, Undergraduate Composites Student	Medium	High
Measure Applied Load	System should be able to measure applied load up to the maximum applied 10kN at a resolution of 10^{-2}N and a minimum rate of 30 times per second	Professor Karanjgaokar, Undergraduate Composites Student	High	Medium
Measure Resulting Strain	System should be able to measure strain of 1µm 30 times per second	Professor Karanjgaokar, Undergraduate Composites Student	High	Medium
Longevity	The device should continue to function within tolerances after a minimum of 2000 complete tensile tests	Professor Karanjgaokar, Aerospace Program / Mechanical Department	Medium	Medium
Fatigue Testing	Force should be able to be applied in up to 30Hz cycles and measured at up to 600Hz to allow for fatigue testing (rapid cyclical loading)	Professor Karanjgaokar	Low	Very High
Control of System	System should be able to be set to various testing modes by a user	Undergraduate Composites Student	Low	Medium
Output of System	System should be able to output experimental results in spreadsheet format.	Undergraduate Composites Student	High	Low
Portability	System should be able to be transported through doorways and elevators	Aerospace Program / Mechanical Department	High	Medium

Power	System should be able to be powered from a standard 120V outlet	Aerospace Program / Mechanical Department	Medium	Medium

Rigidity

Carbon Fiber Reinforced Polymer (CFRP) is very rigid, potentially having 0.5% strain to failure. A compliance with the system allowing 0.01% deformation of the system throughout the testing of the sample will lead to a consistent 2% error, which is acceptable for these uses.

High Force

CFRP has a very high ultimate tensile strength. Professionally made CFRP can have an ultimate strength of greater than 2 GPa. For materials made in an undergraduate laboratory, it is estimated that a strength of 500MPa is possible. For a sample 1mm x 10mm x 5cm and a safety factor of 1.5, this requires a force of 10kN to conduct the tensile test

Sample Size

The system should be able to test samples of CFRP sized 1mm x 10mm x 5cm. This sizing allows for roughly 4 filaments to fit on the sample, enough for the material to behave as a unified composite instead of individual components. However, the size is still small enough to be tested by a 10kN actuation force.

Hold Sample

Along with rigidity, it is critical to fix the sample's edges to the tester in some manner so that the strong 10kN force can actually test the material.

Accept Large Samples

For the sake of research beyond the scope of the undergraduate class, it would be beneficial if the system were able to fit samples of various materials up to 25cm in length

Resolution of Applied Force

In order to produce accurate, smooth stress vs. strain curves, stress must be able to be applied accurately. It should be able to be applied to achieve a minimum strain resolution of 1µm.

Measure Applied Load

To correctly represent results of the experiment, the load applied must be measured accurately. We use this applied load to calculate stress on the sample, half of the stress-strain curve.

Measure Resulting Strain

Similarly, it is necessary to measure strain in some manner to achieve the discussed resolution of 1µm.

Longevity

It is desired that the machine last a *minimum* of 10 years of light use. Assuming 200 uses of the machine per the number of times the class is offered, that results in a minimum of 2000 tensile tests.

Fatigue Testing

Fatigue testing is the application of cyclic loading to the sample in amounts below the ultimate tensile strength until the cyclic loading leads to failure. It is expected that incorporation of this optional design parameter will add significant expense to the project; however, it would be beneficial to the overall utility of the machine. This functionality should be considered but is not required.

Control of System

The user should be able to select a testing mode, press a button to start the test, and then wait as the test is run automatically. However, the system should also allow for full manual control of all components, in case that becomes necessary.

Output of System

After a test is run, it is necessary to provide that data to a user who can then perform additional analysis. Some sort of spreadsheet would be capable of transferring the necessary information.

Power

The power systems available in the lab where this machine would be used are all 120V DC, so the system should be able to be powered from a standard 120V DC power outlet.

1.3.D. Concept of Operations (CONOPS)

The Concept of Operations (CONOPS) looks at the theoretical system from the perspective of a user; in this case, primarily the undergraduate composites student. Through examining different use cases and operational scenarios in detail, a better understanding of the system's function as a whole is gained. This CONOPS primarily explores the two use cases of tensile testing and fatigue testing.

Project Statement

The purpose of this project is to design and deliver a machine to conduct tensile tests on composite materials. The (supervised) undergraduate user should be able to take a handmade sample of CFRP, insert it into the machine, and perform a tensile test. The user should then be able to gather and analyze data from the machine.

Goals and Objectives

Tensile Testing

Achieving tensile testing of CFRP samples is the primary goal of this project. This will be accomplished when samples of the same material are tested in this machine, and in a professionally constructed and used machine, and stress/strain results of testing are found to be within 10%.

Fatigue Testing

If budgetary constraints allow, it is desired that the machine have the ability to perform fatigue testing.

Longevity

It is desired that this machine last a minimum of 10 years with light use or approximately 2000 tensile tests. Further studies are needed to determine how this can best be tested/measured. The design should show the capability for parts to be replaced or upgraded.

Context Diagram

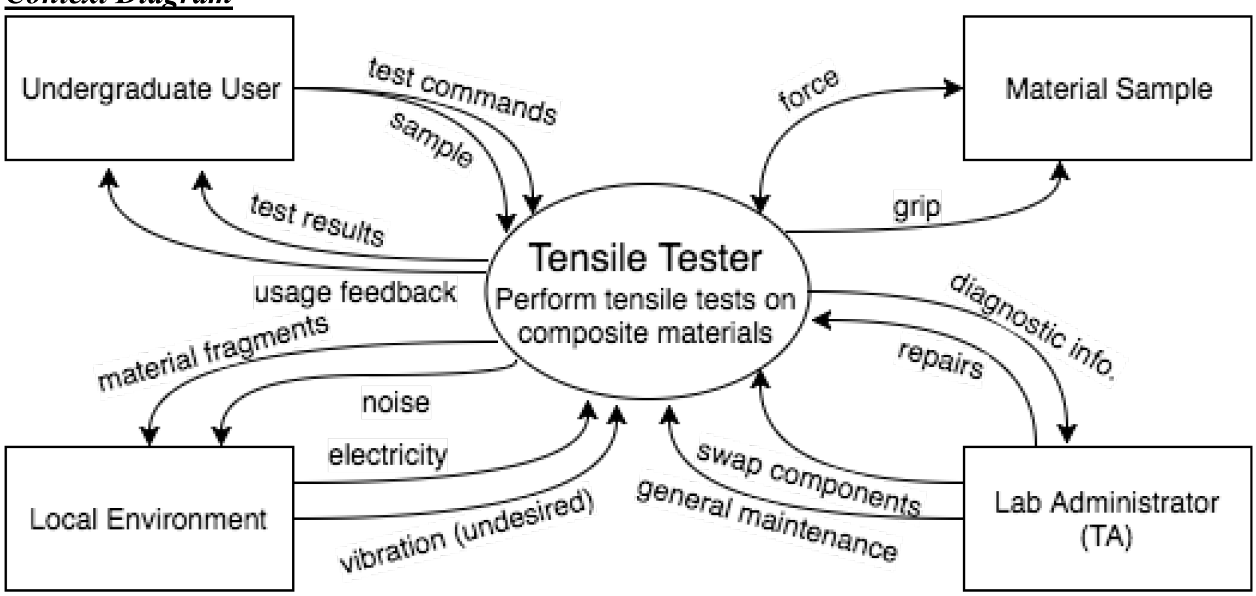


Figure 6. Context Diagram

The Context Diagram (Figure 6) assists in understanding how the proposed system would function as part of its larger system. The primary use of the system comes from the undergraduate user and primary maintenance comes from the lab administrator (TA). It also shows that some undesired flows exist at the interface between the tensile tester and the local environment. Specifically, vibration from the local environment reaching the tensile tester should be minimized, and material fragments from the tensile tester have the potential to enter the local environment in an unsafe manner.

Operating Environment

The system will operate in an undergraduate laboratory, most likely the multipurpose lab: Higgins Labs - Room 216. This lab will have other machinery, such as a small-scale wind tunnel. Furthermore, there will be classes/meetings occurring in nearby rooms, so it is desired that the system not disrupt normal classroom operations with noise or other disturbances. The lab has these features:

- Table (if desired)
- Available 120V power outlets
- 6ft x 6 ft floor space minimum (with ample space to move around)

Beyond the lab, the system will operate within the Higgins Labs building of the WPI campus. There is one large elevator between floors (door: 48" x 84"; weight limit 5000 lbs), and the door to the multipurpose lab (58" x 82").

System Constraints

There are several constraints on the system to be designed:

- It must be within the budget. As the budget is currently undefined, this is one of the team's highest priorities moving forwards to nail down this constraint
- This system must be operable in the WPI environment, by
- The system must be prepared and ready for use by the beginning of D-Term (March 12, 2017)

Use Cases

Table 3. Use Case 1 - Tensile Test

Use Case Identifier	Use Case 1
Use Case Name	Tensile Test
Primary Actor(s)	Undergraduate Composites Student "Student"
Participating Actor(s)	Graduate Teaching Assistant "TA"
Initiating Condition(s)	Student has fabricated a sample of Carbon Fiber Reinforced Polymer (CFRP) and wishes to obtain information about the mechanical properties of the created material, specifically its behavior under applied tensile stress
UC Description	1. Student fabricates a sample of CFRP following directions for a lab for AE4717 - Fundamentals of Composite Materials 2. Student places and secures sample in the machine

	3. Student directs machine to perform a tensile test, under the supervision of TA 4. Machine gradually applies tensile force to sample until reaching failure 5. Student removes fractured sample from machine 6. Machine outputs stress/strain information to user
Alternatives	• (Alternative for 1) Student is provided with / procures a sample
Exit Conditions	• Sample fails (desired exit condition) • Tensile machine recognizes it is reaching its operational limits and ceases test, displaying relevant information to user
Needs/Requirements Discovered	1. Tensile tester should be capable of identifying its current position so it does not exceed its operational limits (i.e. extend too far)
Models/Studies Needed	1. Study: determine all operational limits of tester and ensure tests are ceased when those limits are reached (maximum force, extension, etc.)

Table 4. Use Case 2 - Fatigue Test

Use Case Identifier	Use Case 2
Use Case Name	Fatigue Test
Primary Actor(s)	Undergraduate Composites Student "Student"
Participating Actor(s)	Graduate Teaching Assistant "TA"
Initiating Condition(s)	Student has fabricated a sample of Carbon Fiber Reinforced Polymer (CFRP) and wishes to obtain information about the mechanical properties of the created material, specifically its resistance to applied fatigue
UC Description	1. Student fabricates a sample of CFRP following directions for a lab for AE4717 - Fundamentals of Composite Materials 2. Student places and secures sample in the machine 3. Student directs machine to perform a fatigue test, under the supervision of TA

	4. Machine applies cyclical fatigue loads to sample until reaching failure or another exit condition is reached (see 'exit conditions' below) 5. Student removes fractured sample from machine 6. Machine outputs stress-strain information to user
Alternatives	• (Alternative for 5) Testing must run overnight, so TA will remove sample • (Alternative for 6) Testing must run overnight, so machine must store stress-strain information for student to retrieve at a later time
Exit Conditions	• Sample fails (desired exit condition) • Tensile machine recognizes it is reaching its operational limits and ceases test, displaying relevant information to user • Testing exceeds a predetermined maximum number of cycles or amount of time
Needs/Requirements Discovered	1. Tester should automatically store data for output in case data retrieval is not immediately possible
Models/Studies Needed	1. Study: determine probably length of time for fatigue tests to run in order to better understand and plan for tensile testing use

<u>Summary of System Support</u>

<u>Professor Karanjgaokar</u>

The system will be left under the supervision of Professor Karanjgaokar.

- Ultimate responsibility for all system activities
- Train Graduate Student

<u>Graduate Student</u>

A graduate student will carry out the majority of actual support (under the direction of Professor Karanjgaokar). The student will gain knowledge of the system from both Professor Karanjgaokar, and from this document.

- General maintenance
- Upgrades if desired
- Supervise undergraduate users

Summary of Studies Needed / Discovered

Testing Longevity

One of the system requirements is longevity; however, it is not practical to directly test for this. A study is necessary to determine the best way to test for longevity.

Safety

The interface between the local environment and the tensile tester has the potential for an unsafe flow, where fragments of the tested material could be released into the environment, potentially at high speeds. Further study is necessary to determine how to best mitigate this risk.

Operational Limits

During the design step, the operational limits of the tester should be clearly determined, and design decisions should be made to ensure the system does not exceed these limits (for example the inclusion of limit switches).

Fatigue Test Length

Some fatigue tests in professional applications are run for durations exceeding one week. It should be determined how long is a reasonable length of time for this machine to be used in fatigue testing, to assist in understanding the system's applications

CONOPS Summary

This section detailed the concept of operations of a composite tensile tester designed for AE4717 - Fundamentals of Composite Materials. Through this exploratory process, it is seen that all use cases seem achievable, but there are several details that must be worked out before and during design. The most significant findings are:

- Budget and cost of components will be the primary constraint
- During the design process, special attention must be paid to both determining operational limits and ensuring that the system will not exceed those limits

1.3.E. Summary

The result of this needs analysis is an improved understanding of what parts of the project are necessary, and what is desired.

The basic requirement is for a system that can perform tensile tests by applying forces up to 10kN.

Ideally, the testing apparatus should have fatigue testing capabilities, the ability to test stronger and larger samples, and the ability to gather data with a professional level of accuracy. The testing apparatus should also be designed with ease of actuator upgrade in mind. However, these goals may be unreasonable to achieve under the given conditions.

1.4. Design and Fabrication of Tensile Setup

1.4.A. Requirements

Requirements are the product of the synthesis of all steps up to this point, especially needs analysis. Once requirements are established and agreed upon by shareholders, then design becomes possible.

Functional Requirements

Functional requirements detail what a system must *do* (how it must function) in order to meet the needs of the stakeholders.

Title	Description	Trace to Need	Verification	Priority
Rigidity	System grip area shall move less than 5 μm under 10kN of force	Rigidity	Modeling, testing	Medium
High Force	System shall be able to apply continuous tensile load of 10kN to sample of CFRP	High Force	Modeling, testing	High
Hold Sample	System shall hold sample of CFRP 1mm x 10mm x 5cm without slip when 10kN load applied	Sample Size; Hold Sample	Testing	High
Force Resolution	System shall be able to apply 0.2N increments of force/actuation to create 1μm displacement in CFRP.	Resolution of Applied Force	Testing	Medium
Measure Applied Load	System shall be able to measure applied load up to the maximum applied 10kN at a resolution of 10^{-2}N and a minimum rate of 30 times per second	Measure Applied Load	Testing	High
Measure Resulting Strain	System shall be able to measure strain of 1μm 30 times per second	Measure Resulting Strain	Preliminary testing	High

Longevity	System shall continue to function within tolerances after a minimum of 2000 complete tensile tests	Longevity	Modeling	Low
Fatigue Testing	Force shall be able to be applied in up to 30Hz cycles and measured at up to 600Hz to allow for fatigue testing (rapid cyclical loading)	Fatigue Testing	Testing	Low

<u>Non-functional Requirements</u>

Non-functional requirements are, as the name suggests, requirements that do not directly relate to the functionality of the system.

Title	Description	Trace to Need	Verification	Priority
Emergency Stop	System shall detect when it exceeds operating dimensions and stop immediately	Longevity	Testing	Medium
Control	System shall run full tests unsupervised after user give it simple commands	Control of System	Testing	Medium
Output	System shall record and output force and strain data to a USB storage device	Output of System	Testing	Medium
Portability	System shall fit within a box 5’ wide x 2.5’ deep x 7’ tall	Portability	Measurement	Medium
Power	System Shall power all components off of one standard 12V power outlet	Power	Testing, power usage calculations	Low

1.4.B. High-Level Design

The scope of this project finally reaches the stage where standard engineering design starts working very closely with the systems engineering principles. Tractability and documentation are both critically important pieces in the high-level design stage.

Measures of Effectiveness

The system must test a sample known of CFRP and calculate correct values within a tolerance of 10%

This is how the system will ultimately be judged successful/unsuccessful. A piece of CFRP will be tested in a professional-grade tensile tester, then in our tester. If we get the same values for elastic modulus, ultimate tensile strength, and Poisson's ratio, then the tester can be judged to be successful.

10% error is a very generous tolerance, but this is reflective of both the low budget the project has been allotted and of the low criticality of the tests this machine will be performing.

Measures of Performance

The system must be able to pull a sample of material in tension with a force of 10kN

This is the driving goal of the project. The proposed system is a 10kN tensile tester for composite materials, so it had better be able to test materials in tension with a force of 10kN. The specific 10kN of force is traced back to the desire to test student-fabricated carbon fiber reinforced polymer (CFRP) with an estimated tensile strength of not more than 750 MPa, and a minimum allowable sample cross section of 1mm x 5mm.

The system must not exceed 1% compliance when stretching a sample

When measuring the strain of the sample, it is important that the testing apparatus not take on a significant amount of the strain itself. The system must be very highly resilient to deformation under these high loads.

As with many aspects of this project, this measure will be very difficult to test without assembling the entire machine. If we had an easy way to apply 10kN loads for testing purposes, this project might not be needed. After construction, this could be verified by placing a sample in the tester that will deform a known amount under a 10kN load and compare deformation observed by the machine, with deformation expected based on the known material properties.

Key Performance Parameters

The system must be able to pull a sample of material in tension with a force of 10kN

See the relevant MoP in section 0. This is the point of the system. If it can't accomplish this task, then there was no reason for us to build it in the first place.

The system must measure loads up to 10kN with an accuracy of 0.1% full-scale

The maximum force is the intended rated force of the tensile tester. The accuracy is actually relatively weak reasoning, but it should be good enough for this application, and the accuracy is not too high as to significantly drive the price of the load cell up. High precision is not crucial to the undergraduate lab experience, and 0.1% accuracy is certainly enough to see the shape of the data and make reasonable determinations about the properties of the tested material. This, along with strain, allows us to obtain meaningful information about material properties from the tensile test.

Strain must be measured at a resolution of 1µm

Strain measurement can be done either with extensometers or with a camera and digital image correlation (DIC) software. The value of 1µm is taken from the assumption that CFRP can fracture at strain values as small as 0.005, so with a 5cm sample, that would give us a small enough resolution to get 250 discreet data points

Along with the stress KPP, this is what allows the interpretation of results from the executed tensile test.

Trade Study: Actuation Method

Determining a method of actuation for use in the tensile testing machine was a critical consideration. A trade study was carried out (full details in

) were also considered but were simply too expensive.

As a note, all of these actuators will need to be supported by an electrical system, including a power supply and motor controller. Details of this system are discussed further in chapter 0.Due to the lower cost and potentiometer for additional feedback, the design team chose to use the PA-17P actuator. The requirement of 10kN of force was relaxed to 8.9kN to allow the use of this actuator. This will reduce the maximum testable sample strength, but the stakeholders agreed the reduction was acceptable for the cost and feature benefits.

Grips

Figure 7. PA-17 Heavy Duty Linear Actuator

Figure 8. Force-Test 5K-WC-30 Tensile Testing Grips

Figure 9. Omega S-Beam Load Cell

Grips must be chosen to meet the requirement of holding the sample. They also play a part in rigidity. There were several professionally made grips that were considered. One set of grips is the TAS622 Wedge Grips from Thwing-Albert [9]. These grips have a 10kN rating and pyramid-style serrations to hold the material. The cost was $2425 for a pair of grips, or $570 for just the grip faces.Another set of grips were from Force-Test, the 5K-WC-30 [10]. These grips are capable of holding 5000 lb (22.2 kN) of force and use a rough carbide coating specifically designed for holding carbon fiber laminates. These grips were quoted at $900 for the pair.There was also the option of designing and fabricating custom grips and grip faces. This could be done with the CNC machines in the WPI Washburn Shops. Due to the criticality of the component, and manufacturing complexity of all the other parts to be machined, this was a very possible, but not preferred option. Because of the high performance and relatively low cost, we chose to purchase the Force-Test wedge grips.

Fatigue Testing Requirement Not Met

At this point in the design process, it became clear that the Fatigue Testing requirement could not be met with the given budget. The primary issue was the lack of an acceptable actuation method that could achieve both fatigue and tensile testing

If this functionality is needed in the future on a slightly higher budget, a possible way to achieve this without enormous expense is by using a piezoelectric actuator to apply the fatigue loads in conjunction with an electromechanical actuator to apply the standard tensile load. The linear actuator can apply forces and displacements necessary for tensile testing but is not capable of fatigue. The piezoelectric actuator can apply fatigue loads but has an actuation distance of only 32µm. It seems possible to set up both of these actuators in series and carefully control them to achieve both fatigue and tensile testing capabilities. This setup could result in a total actuator cost on the order of $3,000, compared with $25,000 for a fatigue-rated electromechanical actuator, or $85,000 for an “inexpensive” hydraulic actuation system that meets our design requirements.

After conferring with the primary stakeholders, these shortcomings were expressed, and the decision was made to continue with the project with a reduced scope of only tensile testing.

Load Cell

From the requirement for measuring applied load, it is desired to measure load up to 10kN at a resolution of 10^{-2} N. This requires a load cell with an accuracy of 0.001%. One load cell considered was the Omega LC101-2.5K for $360. It had an accuracy of 0.1% [11]. Another option was the LC204-2.5K from Newport for $550 [12]. This load cell would support fatigue testing, but accuracy was also listed at 0.1%. The Honeywell Model 41 was priced similarly [13].

It was determined that finding a load cell within the full project budget of $3000 would not be practical, and one of the load cells with an accuracy of 0.1% would provide *acceptable*, but not great quality results. At this point, it had been determined that the actuator would not be able to support fatigue testing, so it was not necessary to have a load cell capable of fatigue. Therefore the inexpensive and reasonably accurate Omega LC101-2.5K was chosen.

Summary

This section detailed the selection of non-structural components for the tensile tester, based on the determined requirements. These component selections are summarized in

Table 5.

Table 5. Summary of selected non-structural components

Part	Manufacturer	Part Number	Description	Cost
Actuator	Progressive Automations	PA-17P	12” 2000lbs linear actuator with potentiometer	$405*
Grips	Force-Test	5K-WC-30	Tensile Testing Wedge Grip	$900

Load Cell	Omega	LC101-2.5K	2500 lbs S-beam load cell	$360

*Note: $405 is the standard retail price. The price the design team paid is $300 due to purchasing an actuator from a canceled order.

1.4.D. Low-Level Design: Structural Design

After all components of the test column were determined, and structural requirements were outlined, the design of the tensile tester structural frame began. As discussed earlier in the paper, the structural frame was initially intended to support a testing column applying a 10 kN force while deforming no more than 5 μm. Over time, the deformation requirement was relaxed to allow for a smaller structural frame that would be less expensive, and reduce machining complexity.

Design Philosophy

Usability

During the design process of the testing apparatus, ease of use was kept in mind. To conduct a test, the user should feel that operation of the machine is natural. A primary design decision that affected the usability of the machine was the incorporation of a bottom mounted actuator. Initially, the actuator was mounted on the top plate, positioning the grips at floor level. This would cause the user to crouch or lay down to insert a CFRP sample in the grips. To address this issue, the actuator was mounted on the bottom plate. Mounting the actuator on the bottom plate positioned the grips four feet above the ground. Mounting the actuator on the bottom plate required the utilization of a moving middle plate to align the test column, which was deemed acceptable to incorporate for added user-friendliness.

Machinability

The machinability of individual components was considered a priority in the design of the structural frame. Minimizing the required machining allowed the majority of the structural frame components to be fabricated by the design team at the WPI Washburn Labs. Outside machining costs for the structural frame was quoted at $5000, making machining at WPI a necessity.

Over time, the design team placed more emphasis on machinability. This is due to suggestions from Professor Karanjgaokar and Anthony Linn. Early designs of the structural frame incorporated multiple support columns and complex middle plates. This was meant to cut material cost, as the wide diameter support columns required for a two column system were determined to be the most expensive component. While utilizing multiple smaller diameter steel columns would save money in material costs, the machining costs of the plates would negate any financial benefit.

The base plate design also changed drastically to improve the machinability of the design. In early versions, the baseplate was intended to be H shaped and machined out of a large piece of carbon steel. This design would require a large amount of material to be removed from the carbon steel block. The final design utilizes a smaller block that only requires drilling for posts and fixtures, with prefabricated box channels acting as the “wings” of the H shape for stability. This reduces cost and timeliness of machining.

The requirements for maximum deformations were relaxed allowing the size of the structural frame to be reduced. The final structural frame deflects 50 microns at the center of the top plate. This was deemed to be an acceptable amount of deformation, as it would not drastically affect the test data.

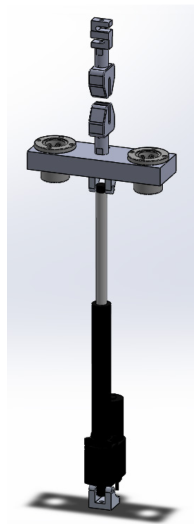
Reparability

If a testing apparatus component or fixture fails, the machine would have to undergo repairs. The design team attempted to minimize the cost of repair upon failure of the testing apparatus. Most fixtures on the test column and structural frame utilize ½ “x 20 threaded bolts, allowing for simple replacements. Most bolts and washers were required to be purchased in multiples, meaning that spares will already be in storage.

The choice of actuator also lends itself to reparability of the testing apparatus. The Progressive Automations PA-17 actuator purchased for use in the testing frame is under warranty. If an actuator failure occurs, this component can be replaced with no cost to the Aerospace Engineering Department.

Test Column

The test column is the machine assembly consisting of the PA-17 actuator, Force Test grips, Omega LC101-2.5K load cell, and fixtures. The actuator is mounted to the base and mid-plate using the BRK-17 bracket. The mid-plate is allowed to move along the support columns with the use of two linear bushings. The mid-plate also acts as a fixture between the actuator and Force Test grip. A ½ “x 20 threaded hole is bored in the center of the mid-plate. ½” x 20 threaded rods are utilized for the fixture of each component. Separate threaded rods are used to allow for the grip to be aligned properly without affecting the adherence of the bracket to the plate. All components and fixtures utilize ½” x 20 for simplicity of assembly and parts acquisition.



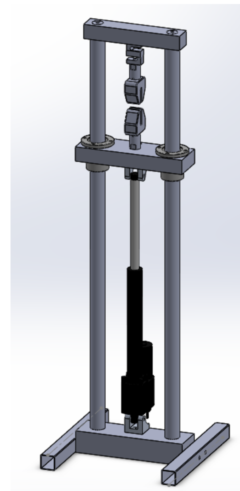


Figure 10. Test Column Model **Figure 11. Tensile Testing Apparatus**

<u>Overall Structure</u>

The final structure, pictured in Figure 11. Tensile Testing Apparatus, was determined to be suitable for supporting the test column and the forces it applies through analysis in SolidWorks. Buckling and static analysis' were performed on the structure frame model. A 10kN force was applied in a downward direction at a central point on the top plate. This point is where the test column connects to the top plate. The base of the bottom plate was assumed to be fixed geometry. Table 6 outlines properties of the structural frame found from the previously mentioned test. The final testing structure has a footprint of 19" x 30" and a height of 59.5".

Table 6. Structural Frame Properties

Properties	Value	Units
Weight	178.23	lbs
Minimum Static Factor of Safety	4.17	-
Buckling Factor of Safety	17.366	-
Maximum Deflection	50	µm

Screenshots of test results are located in Appendix B.2.

1.4.E. Fabrication and Assembly

After the design team consulted with the project advisor professionals and determined the structural frame design was satisfactory, a machining strategy was formulated. The design team spoke with Ian Anderson, the Senior Instructional Lab Technician at WPI's Washburn Shops, and

Tolerances

Tolerances of the machined surfaces and bored holes were determined using the Machinery's Handbook [14]. Through the information gathered in the handbook, and with the assistance of the Instructional Lab Technicians at WPI's Washburn Shops, proper tolerances were determined.

Plates

The top, mid, and base plates were machined at WPI Washburn Shops with the help of Instructional Lab Technicians. CAM Wizard was used to create the tooling path of the CNC machine for efficient fabrication of all components. These components were machined over the course of two weeks at the beginning of D term 2018.

Posts

Surface hardened linear shafting was purchased from McMaster-Carr and machined to fit the design specifications outlined by the design team.

Assembly

The assembly process of the tensile testing apparatus is as follows:

1. The base plate is placed on its side
2. The support columns reduced diameter ends are seated into the corresponding holes in the base plate
3. The support columns are secured to the base plate using 2" long ½" - 20 threaded bolts, 2" diameter metal washers, and vibration dampening washers
4. The BRK-17 bracket is secured to the base plate using 4 ¾ " long ½" - 20 threaded bolts, nuts, lock washers, and vibration dampening washers
5. The assembly is carefully tipped to sit on its base using leverage from the posts
6. The base plate supports are affixed to the sides of the baseplate using four 3" long ½" - 20 threaded bolts
7. The mid-plate assembly is constructed using the following procedure:
    a. Ensure flanged linear bushings are lubricated to factory specifications
    b. The flanged linear bushings (with the flange facing up) and line up the threaded holes to the corresponding holes in the mid-plate
    c. The flanged linear bushings are affixed to the mid-plate using eight 1" long 5/16" – 18 x hex head screws

    d. The second BRK-17 bracket is affixed to the mid-plate using a 1.5” long ½ “ - 20 threaded rod and nut for the central hole, and a 2.5” long threaded bolt and nut for the outer hole
    e. A 1.5” long ½“- 20 threaded rod is threaded into the center hole from the top face of the mid-plate. Approximately 1” of the rod is left to protrude from the top face
    f. The Force-Test grip is threaded onto the protruding rod. The grip is ensured to be perpendicular to the front facing side of the plate
8. The actuator is fixed to the bottom plate bracket using the BRK-17 bolt
9. The mid-plate assembly is slid on to the support columns from the top and held approximately 2 feet above the base plate
10. The actuator is held in an upright position and the mid-plate assembly is lowered so the mounting hole on the actuator and bracket are aligned
11. The actuator is fixed to the middle plate bracket using the BRK-17 bolt
12. The top plate assembly is constructed using the following procedure:
    a. The load cell is fastened to the top plate using a 5.5” long ½ “ - 20 threaded rod
    b. The second Force-Test grip is fastened to the load cell using a 1.54” long ½“ - 20 threaded rod. The grip is ensured to be perpendicular to the front facing side of the plate
13. The top plate assembly onto the support column using the corresponding holes
14. The support columns are secured to the top plate using 2” long ½” - 20 threaded bolts, 2” diameter metal washers, and vibration dampening washers

1.4.F. Control System

The control system is critical to achieving the functionality of a tensile tester. This system manages the actuator and records the data needed to create stress-strain curves, the ultimate goal of a test with this apparatus.

Computer

The computer used for this application is a Dell Optiplex 7010. Performance is not a key characteristic in this decision, but very low specs would result in some frustrations from the machine operators.

Virtual Instrument

The Tensile testing apparatus is primarily operated via a LabVIEW Virtual Instrument (VI). This VI allows the user to manually adjust the position of the linear actuator. It also reads out useful diagnostic information:

- The linear actuators current extension (from the potentiometer)
- The current recorded force (from the load cell)

- Any warnings (such as unresponsive sensors)

When the user begins a test, the VI directs the linear actuator to apply a slowly increasing amount of force, to create an increasing stress. The recorded stress over time (along with other information for debugging) is saved in a .csv file. When the system detects a fracture (as evidenced by a sudden release of stress) the system stops and declares the test complete. And of course, for safety, there is a large emergency stop button, which immediately halts the motion of the linear actuator in place.

Data Acquisition

The VI interacts with the physical apparatus through a National Instruments Data Acquisition Unit (DAQ). In particular, this system uses the NI-PCIe-6361, which connects to the computer's PCIe port. This device handles both input to, and output from the VI. The I/O ports on the DAQ are broken out by an SCC-68 terminal block [15]. An SCC-SG24 Load Cell Input module is used to supply excitation voltage to and read signal from the load cell. Potentiometer readings from the actuator are collected from an analog input pin on the SCC-68. And commands to the actuator are sent out via a pulse-width-modulation (PWM) signal sent from the DAQ to the motor controller.

These data acquisition components were used because they were on hand. It is important to have some way to condition the signal from the load cell so that it can be read as accurately as possible. This is done by the SCC-SG24 module but could be done by any number of other components.

Strain Measurement

Strain measurement is done using a USB camera recording images. The frames are post-processed with the digital image correlation (DIC) software Vic-2D. This software allows a strain resolution of as low as 10 microstrains to be measured [16]. The resulting strain data is then compared with the collected force data to create stress-strain curves.

An area of future research could be integrating the strain measurements more fully with the rest of the machine, or somehow implementing digital image correlation through LabVIEW. The project team investigated this and determined it to be theoretically possible, but very difficult.

Motor Controller

The actuator is controlled by a Victor SP motor controller. The Victor SP receives a PWM signal from the DAQ; this signal tells the controller how much power to give the actuator. The Victor SP then controls the speed of the motor with pulses of power at a frequency of 15kH. These pulses functionally make it such that the actuator is receiving less than full power, and therefore pulls with less force [17]. The Victor SP receives the power to give the motor from the 12V/20A power supply discussed later.

Power Distribution

One of the requirements was that the tensile testing apparatus be able to be powered from a standard 120V outlet. To this end, a power distribution system has been developed. The computer and monitor use standard power outlets from a power strip. The camera is powered from a USB port on the computer, and the NI-DAQ is powered via the PCI slot on the computer. The actuator (through the motor controller) has different power requirements. It needs up to 20A at 12V. This power is provided by a simple power supply (Padarsey S120-240-20A) which draws power from a standard 120V outlet on the power strip.

1.5. Conclusions and Recommendations

The project set out to fill the need for a low-cost, high-strength tensile tester. Through careful use of engineering skills, the project team delivered an apparatus capable of testing samples of CFRP and creating acceptable stress-strain curves.

1.5.A. Final Cost Breakdown

As cost was the primary driving factor for the majority of design decisions, the cost breakdown is one of the primary products of the design effort. The completed tensile testing machine cost a total of $2,922.27. This is a significant cost reduction from commercial tensile testing machines, as shown in chapter 0. The complete cost breakdown of the testing apparatus is shown in Table 7.

Table 7. Final Cost Breakdown

Component	Part Name	Part Number	Supplier	Cost Per unit	#	Total Cost
Grips	5,000lbs Tensile Testing Wedge Grip	5K-WC-30	Force-Test Inc.	$459.25	2	$918.50
Actuator	PA-17 Heavy Duty Linear Actuator (with potentiometer)	PA-17-12-2000	Progressive Automations	$280.00	1	$280.00
Actuator Bracket	PA-17 Mounting Bracket	BRK-17	Progressive Automations	$23.99	2	$47.98
Motor Controller	Victor SP	217-9090	Vex Robotics	$69.37	1	$69.37
Power Supply	Padarsey Universal Regulated Switching Power Supply	ASIN: B06WPBF494	Amazon	$15.99	1	$15.99

Load Cell	S-Beam Load Cell	LC101-2K	Omega	$358.04	1	$358.04
Column end bolt	½”-20 x 2” Bolt (5 Pack)	91251A020	McMaster-Carr	$6.73	1	$6.73
Bolt Baseplate to Actuator	1/2"-20 X 4-3/4" Bolt (1)	91257A174	McMaster-Carr	$3.78	2	$7.56
Metal Washers for column	ID-0.5" OD-2" washer (5 Pack)	91525A150	McMaster-Carr	$6.59	1	$6.59
Vib Damp Washer for Columns	ID-0.75" OD-2" Vib. Dampening Washer (10 Pack)	90131A106	McMaster-Carr	$6.24	1	$6.24
Vib Damp Washer for everything else	ID-0.53" OD-1" Vib. Dampening Washer (5 Pack)	93650A195	McMaster-Carr	$7.23	1	$7.23
Threaded Rod (Bracket Center Hole to Midplate & Midplate to Grip)	1/2"-20 x 1.5" Threaded Rod	90322A161	McMaster-Carr	$3.57	2	$7.14
Bolt (Bracket to Midplate)	1/2"-20 x 2.5" Alloy Steel Socket Head Screw	90044A171	McMaster-Carr	$3.68	1	$3.68
Threaded Rod (Grip to load cell)	1/2"-20 x 2" threaded rod	90322A162	McMaster-Carr	$3.80	1	$3.80
Bolt (Load Cell to Top Plate)	1/2"-20 x 5.5" threaded rod	92620A755	McMaster-Carr	$6.33	1	$6.33
Bolt (Baseplate Support to Baseplate)	1/2"-20 x 4" bolt	92620A752	McMaster-Carr	$6.04	4	$24.16
Nut	High-Strength Steel Hex Nut 1/2"-20 (50 Pack)	94895A825	McMaster-Carr	$8.54	1	$8.54

Linear Bearing	Flange Mounted Linear Ball Bearing 2"	6483K59	McMaster-Carr	$185.63	2	$371.26
Linear Bearing Screws (to Midplate)	5/16"-18 x 1" Alloy Steel Socket Head Screw (50 Pack)	91251A583	McMaster-Carr	$10.56	1	$10.56
Support Column	60" 1566 Carbon Steel Linear Shafting	6061K88	McMaster-Carr	$271.51	2	$543.02
Bottom Plate	3" x 4-1/2" x 15" C-1018 CF Carbon Steel	-	Peterson Steel Corporation	$120.00	1	$120.00
Mid Plate	2" x 5" x 15" C-1018 CF Carbon Steel	-	Peterson Steel Corporation	$70.00	1	$70.00
Top Plate	2" x 2-1/2" x 13-1/2" C-1018 CF Carbon Steel	-	Peterson Steel Corporation	$30.00	1	$30.00

1.5.B. Recommendations for Future Study

Due to time constraints, this project was unable to test the machine fully. It would be beneficial to conduct comprehensive tests using many samples, and comparing results against those of a professional-grade tensile tester.

Other possible improvements that were discovered during this project include: adding a piezoelectric actuator to the apparatus to allow for fatigue testing and integrating the digital image correlation strain measurements more closely with the LabVIEW Virtual Instrument that controls the tests.

2. DYNAMIC TESTING SETUP- SPLIT HOPKINSON PRESSURE BAR

2.1. Introduction

What does a Canadian goose piercing the hull of a commercial airliner, a Kevlar vest catching a bullet, and even you slipping and falling while reading this paper have in common? Each of the aforementioned scenarios is an example of dynamic stress, or the loading of forces from one object onto another at a very high strain rate. Specifically, dynamic stress is occurring at the point where the bird makes contact with the hull, the bullet with the Kevlar vest, and your body with the ground. Now, why is dynamic stress important and how does it apply to the world of professional engineering?

The world witnessed its first take off in 1903 with Orville and Wilbur Wright's *Flyer*, comprised only of spruce wood, cloth, and an aluminum engine [23]. More than a century later Boeing's 787, a commercial airliner, is comprised of 15% Titanium 20% Aluminum and 50% advanced composites, a demonstration of the advancements in the field of aviation since these humble beginnings [24]. However, as scientists and engineers work together to construct larger and more durable aeronautic and astronautic vehicles, it is necessary to test and fully understand the limits of durability, longevity, and mechanical response of the constituents materials.

The Aerospace Industry utilizes a variety of testing apparatuses to analyze the dynamic response of materials by simulating impact conditions [23, 26-37]. Of these various methods, the Split Hopkinson Pressure Bar (SHPB) is more commonly used in aerospace applications. The SHPB tests the mechanical behavior of materials experiencing dynamic stress through one-dimensional elastic wave propagation theory, described in further detail later in this paper. To conduct an experiment, a gas gun is filled with air to a desired pressure. Next, a striker bar is fired linearly from the gun contacting the incident bar. This contact induces an elastic wave, which propagates along the bar until it reaches the test specimen. Upon contact, some of this wave is reflected back along the incident bar, some is absorbed by the material, and some is transmitted along the transmission bar. Then, strain gauges, mounted on each of the incident and transmission bars, measure the one-dimensional elastic strain waves which are recorded on an oscilloscope.

The SHPB used in this paper contains a carefully aligned single stage gas gun to ensure the accuracy of the projectile (striker bar). A 0.75 inch diameter 0.062 inch thick multipurpose 110 copper pulse shaper is used to mitigate some of the dispersion effects from the impact. The apparatus has 0.740±0.0001 inch diameter incident and transmission bars of Maraging 350 steel and 7075-T651 aluminum. The strain gauges are in a half-bridge configuration and connected to the power supply, amplifiers, and oscilloscope via BNC connectors. The data collected from the oscilloscope is processed with a MATLAB script for analysis.

2.2. Literature Review

2.2.A. Justification

The Split Hopkinson Pressure Bar (SHPB) is a tool used to measure the response of a material subjected to high rates of strain. Using the SHPB engineers and material scientists can dynamically test engineering materials in order to ascertain the compressive stress-strain relationship of the material beyond the data collected using conventional material testing machines [28]. Understanding a material's response to dynamic stress is paramount to ensure product reliability under rapid loading conditions such as an aircraft bird strike.

John Hopkinson

In 1872, John Hopkinson devised an experiment to rupture an iron wire using a drop weight as shown in figure 12. Using his experimental results, Hopkinson published two papers describing the strength of the iron wires under different loading conditions. He also described the theory of propagating waves through an iron wire fixed at one end, and the other suddenly loaded under tension by an impact from a moving mass. Hopkinson used his experiments to study whether the iron wire would rupture near the impulse end or near the fixed end. He determined to break the wire near the mass required an impact velocity of twice that of the fixed end.

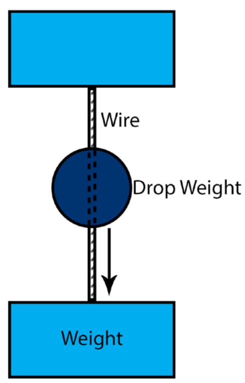


Figure 12. John Hopkinson's Dynamic Stress Apparatus [28]

Bertram Hopkinson

Bertram Hopkinson revisited his father's work and in 1914 he developed an experimental process called the Hopkinson Pressure Bar. The Hopkinson Pressure Bar was an experimental procedure to measure the pressure produced during the impact of a projectile. Through experimentation, Hopkinson discovered if a bullet were fired against a rod, an induced pressure pulse would propagate along it. A tension pulse would be reflected back from the free end of the rod. Hopkinson described how the momentum of the direct wave would be trapped by a smaller rod of the same cross-section and material and this smaller rod would fly off the main pressure bar. A ballistic pendulum measured the momentum of this separated piece. Since the mass of the ballistic pendulum was known, when Hopkinson measured the maximum period and displacement he could calculate the momentum of the separated piece. Through his experiments, Hopkinson proved by varying the length of the separated piece and measuring the subsequent momentum he could measure the total duration and maximum amplitude of the pressure. His experiments did not however allow him to obtain a perfect pressure pulse shape.

Davies

Approximately 34 years after Bertram Hopkinson developed his Pressure Bar, Davies developed the first radial and dynamic axial strain measurements using a Hopkinson Pressure Bar experiment. To accomplish this, Davies used the Hopkinson Pressure Bar technique with a parallel plate, cylindrical condensers, and an oscillograph. The apparatus looked similar to the modern setup, minus the transmission bar. In addition to further developing the measurement techniques, Davies identified two main disadvantages to the Hopkinson Pressure Bar technique. The first disadvantage was that the experimenter could not obtain an accurate pressure-time history. The second disadvantage was the end-piece adhesive force limited the minimum pressure that could be accurately measured.

Through his experiments, Davies was able to conclude five critical facts about the Hopkinson Pressure Bar method. The first was the Pressure Bar is not capable to accurately measure pressures subject to changes of time in the order of 1 microsecond. The second was when the applied force changes from zero to the finite value; it takes a finite amount of time for the pressure from the displacement at the measurement end to become an approximately constant value. The amount of time it takes depends on the radius and length of the bar as well as Poisson's Ratio. The third conclusion was that when the force was decreased from a finite value to zero, it would take a finite amount of time for the pressure from the displacement to drop to its approximate constant value. The fourth conclusion was measurement accuracy could not be guaranteed if the force applied rises instantaneously from zero to a finite value then is held at that value for a period of time in the order of nanoseconds before dropping instantaneously to zero. The fifth conclusion Davies made was the accuracy of the derived pressure increases as the constant or slowly varying force is maintained for a longer period of time since the derived pressure fluctuations decrease as time increases.

Kolsky

In 1949, Kolsky was the first to adapt the Hopkinson bar technique to measure a material's stress-strain response while that material was under impact loading conditions. Kolsky used a similar experimental set up to Davies, however Kolsky placed the specimen between two bars as in the modern setup. Kolsky did several experiments measure the mechanical properties of different materials using a modified Hopkinson Pressure Bar. Kolsky's modified Hopkinson Pressure Bar became known as a Kolsky Bar or a Split-Hopkinson Pressure Bar (SHPB). Over the course of his experimentation, Kolsky learned many things. The first was in order to neglect axial inertia in the specimen, the specimen must be thin. Kolsky found if the interfacial frictions were not minimized by the use of lubricant, the experiment required a larger than expected loading stress to measure strain and the interfacial frictions led to uncertainty in the measured stress-strain response. Thus, lubricant was necessary to decrease the interfacial frictions between the specimen and the bars. Kolsky also learned smaller specimens should be utilized in order to minimize the radial inertia since radial inertia is proportional to the specimen's radius squared.

2.2.B. Modern Setup of the Apparatus

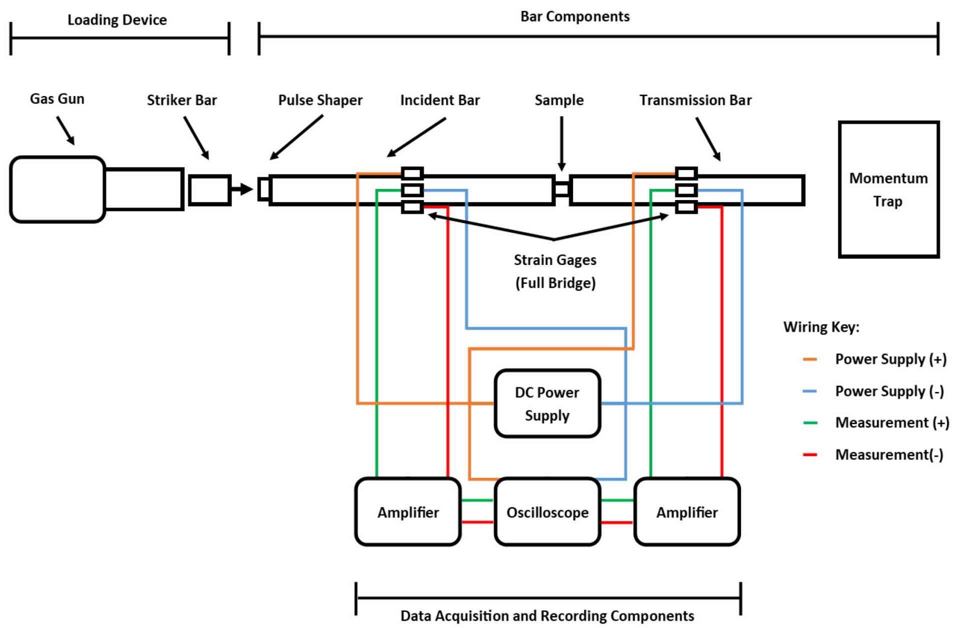


Figure 13. Modern Split Hopkinson Pressure Bar

The setup of a Split Hopkinson Pressure Bar (SHPB) is simple in theory. The basic components are a loading device, incident bar, transmission bar, strain gages, a momentum trap, and, of course, the sample. This SHPB uses a gas gun to accelerate the striker bar. The striker bar collides with the incident bar, sending a compressive strain wave along the incident bar. A pulse shaper is often used to reduce dispersion. The compressive strain wave propagates along the incident bar until it reaches the sample. When the compressive strain wave reaches the sample, a portion of the strain wave is absorbed by the sample, a portion is transmitted through the transmission bar, and the remainder is reflected back through the incident bar. The momentum trap absorbs the excess linear momentum of the transmission bar to prevent additional, reflected strain waves. The strain gages on the incident and transmission bars measure the incident, transmitted, and reflected strain waves. The power supply sends the excitation voltage to the strain gages. The amplifiers are used to increase the resolution of the minute voltage changes of the strain gage signal. The oscilloscope records this amplified signal as well as the voltage from the power supply. This layout is depicted in figure 13.

The gas gun is designed to fire the striker bar at a consistent and measurable velocity making the experiment repeatable. The gun is comprised of a chamber, a barrel, charging and discharging valves, pressure gages, a rapid discharge plunger mechanism, and a muffler. To operate the gas gun, the charging valve is opened and the gun is pressurized using an external air compressor. When the desired pressure is reached, the charging valve is closed and the compressor is disconnected and shut off. Dangerous areas near the Split Hopkinson apparatus are cleared of personnel before firing. To fire the gas gun, the discharging valve is opened rapidly, creating a pressure differential across the plunger mechanism. This causes the plunger to retract and uncover the barrel, releasing the pressurized air down the barrel, firing the gun. The air forces the striker bar and sabots out of the gun at a velocity up to 100 meters per second. The gas gun is a safer and more predictable replacement for the explosives from the original Kolsky Bar (1949).

A pulse shaper is used to reduce the noise and dispersion effects from the collision of the striker bar into the incident bar. Pulse shapers can be made from a thin copper disk, paper, or anything that proves to mitigate these effects during experimentation. The pulse shaper rests against the leading face of the incident bar and is impacted by the striker bar to "shape the strain pulse" and transmit this smoother wave along the incident bar.

The general consensus for Split-Hopkinson pressure bar design has three simple criteria:

- The transmission bar is at least twice the length of the striker bar.
- The minimum length of the transmission bar is twenty times the bar diameter.
- The incident bar is twice the length of the transmission bar [28].

In this setup, the original, nominal, bar diameter was 0.75 inches. This required minimum lengths of the incident and transmission bars to be 30 inches and 15 inches respectively. The lengths of 72 inches for the incident bar and 36 inches for the transmission bar were set to accommodate a striker bar maximum length of 18 inches. The striker bar length directly affects the amplitude and length of the stress wave. Longer striker bars are used for softer materials while shorter bars are used for stiffer materials. The stiffer a material, the more its stress-strain response is dominated by the linear elastic region over smaller strain region. Softer materials often have elastic and plastic responses which occur non-uniformly over much greater strain magnitudes, this requires a longer wave [28].

The specimen is cylindrical in shape and smaller in diameter than the diameter of the bars. The specimen needs to be thin enough to neglect both axial and radial inertia. The specimen needs to be short enough to ensure there is compression, not bending or buckling. The specimen needs to be long enough so the strain rate is not too high. The most common length-to-diameter ratio is sqrt(3)/4 to satisfy the aforementioned criteria. The specimen needs to be extremely well lubricated and fit snugly between the incident and transmission bars. The lubrication is necessary because as the length of the specimen is compressed, the diameter expands in accordance with the Poisson's effect, excess friction results in barreling of the sample.

The momentum trap consists of a clay block, backed by rubber, wood, and steel. The clay absorbs the majority of the momentum by deforming. The rubber absorbs the majority of the remaining momentum. The wood absorbs the small amount of unabsorbed momentum and the steel braces the structure. The momentum trap is important because extraneous wave reflections can interfere with the strain wave data. The momentum trap also prevents ricochet and contains the transmission bar for safety.

The strain gages are placed on the incident and transmission bars to record the incident, transmission, and reflected wave. The strain gages are located such that the reflected pulses do not overlap. These locations can be determined using the pulse length and the wave speed through the bar. The pulse length is determined experimentally and the wave speed equation is below. This equation can be used for estimations, but once the gages are placed, this speed can be measured experimentally.

$$C_0 = \sqrt{\frac{E}{\rho}} \tag{1}$$

The strain gages used in this setup are Omega brand with 120Ω ± 0.3% resistance and have a gage factor of 2.14. The strain gages are in a half bridge configuration and spread in an equidistant configuration around the circumference of the bar. Each gage was wired into opposite branches of the Wheatstone bridge and gages of the same resistance, but located off the bar and unstressed, were used to balance the bridge. Gages on opposite sides of the bar cancel out some of the minor bending and torsional effects of the strain wave. This ensures that only the one-dimensional compressive strain wave is being measured. The gage locations and half-bridge configuration are depicted in the figure 14 below.

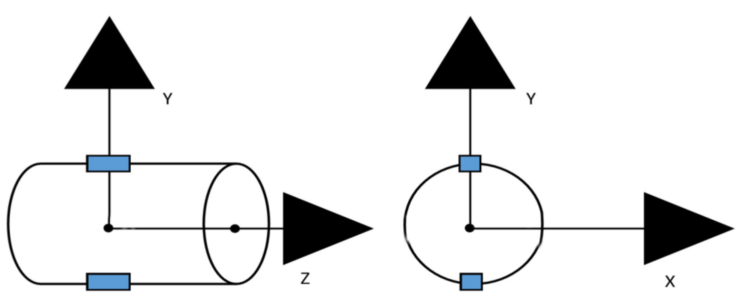


Figure 14. Strain Gage Locations

The expected maximum reflected strain signal can be calculated from the strain rate, wave speed, sample length, gage factor, and excitation voltage. The equations are shown below:

$$\varepsilon_r = \frac{\dot{\varepsilon}}{-2 * C_0 * l_{sample}} \tag{2}$$

$$V_{out} = -GF * V_{ex} * \varepsilon_r \tag{3}$$

Since the expected output is on the order of millivolts, an unamplified signal will have poor resolution. The oscilloscope used in this setup has a maximum input voltage of ten volts. To better utilize this range and improve the resolution, the strain signal must be amplified. It is worth noting that as the gain increases, measurement noise also increases because the aggregate signal is amplified. The precise gain settings for materials will be determined experimentally to balance low noise with a high resolution. For the steel sample measured in this experiment, a gain of 51 was used. This amplified the strain signal to the order of tenths of volts, easily measurable by our oscilloscope. The resulting output also contained a low amount of noise and was not too large so that it would be clipped by the range limitations of our amplifier.

Since the wave speed is on the order of thousands of meters per second, a rapid data acquisition device must be used. An oscilloscope is a perfect candidate to record this high-speed wave. The oscilloscope being used in this setup is a Tektronix MDO3024. The MDO3024 takes measurements at a rate of up to 200 MHz and has a 16-bit resolution. The oscilloscope has four analog channels: one for the strain gages on the incident bar, one for the strain gages on the transmission bar, one for the excitation voltage at the incident bar, and one for the excitation voltage at the transmission bar. The oscilloscope saves the data to external memory, which can then be exported to a computer for further processing and analysis.

2.2.C. Assumptions for a Valid Experiment

The calculations used to determine stress and strain characteristics of the specimen rely on five critical assumptions. Failure to validate these assumptions will result in poor experimental results. The five assumptions are as follows. One, stress wave propagation through the bars must be one-dimensional. Two, the interfaces between bars and specimen must be planar. Three, the specimen must be in stress equilibrium, following a brief 'ringing up' period. Four, assume that the specimen is incompressible. Five, frictional and inertial effects must be minimized to the point of negligibility. The consequences of invalid assumptions and methods to ensure proper experimental setup are discussed below.

The stress wave traveling through the incident bar, transmission bar, and specimen must be a one-dimensional wave. To achieve this outcome, all aspects of the experiment, from the gas gun to the transmission bar, must be aligned to a very high degree of accuracy along a single axis. In addition to this, properties of the incident and transmission bars can be optimized in order to help ensure this effect. In general, the greater the length to diameter ratio, the more one-dimensional the stress wave propagation can be assumed to be. Increasing the length to diameter ratio reduces the influence of Poisson's effects, thereby reducing the radial deformation of the bar [28]. Additionally, close to the ends of the bars, stress is not uniformly distributed radially. This becomes an issue in determining the locations in which to place strain gages, as strain gages are mounted only to the surface of the bars. Mounting strain gages farther from the ends of the bar mitigates this effect as the stress values become evenly distributed. Literature suggests placing strain gages at least ten bar diameters away from the specimen, or at the midspan of a bar, which is at least twenty bar diameters in length [28, Pg.38].

Assumption number two, a planar interface between the bars and specimen, follows the trend of the previous assumption of proper experimental alignment. There are two main ways non-planer contact between bars and specimen can occur. The first is simply if the ends of any component are poorly designed or machined such that the end surfaces are not circular and perpendicular to the length of the bar. The second way in which this assumption can be invalidated could occur even if the bar-specimen interfaces begin the experiment in a planar fashion. If the stiffness of the specimen is much greater than the bars, the specimen may create an impression in the bars subsequently ending the initial planar condition [28].

The typical reading from a strain gage attached to either the incident or transmitted bar shows a roughly trapezoidal pulse [37]. However, following the initial rise, the strain reverberates slightly before settling to an equilibrium state. This reverberation is often referred to as the 'ringing up' period. Only after this period is the specimen assumed to be in stress equilibrium. It is difficult to determine a specific instance when this assumption is met but some literature suggests after five or so 'rings' the specimen has roughly equal stress on both ends [37]. Apart from analyzing the data following the experiment, this ringing period can be accounted for in part using a pulse shaper, typically a soft metal that deforms between the striker bar and incident bar. Pulse shapers can alter rise time, pulse shape, reverberation, and dispersion. Using a thinner specimen can also reduce the ringing up period simply since the wave must travel a shorter distance each reverberation.

The assumption of incompressibility can't be ensured through experimental setup as it is a property of the specimen's material. Compressibility can only be controlled through selection of specimen materials. The assumption of incompressibility ensures constant material properties such as density in the experiment.

The last assumption requires that frictional and inertial effects in the specimen are minimized. Incompressible specimens have the tendency to deform radially if strained axially due to Poisson's effects. Friction at the ends of the specimen can restrict this deformation and create a barreling effect. To avoid frictional effects, ends of bars and specimen must be precisely machined and properly lubricated. Frictional effects also become more significant as the thickness of the specimen decreases. [28]. Inertial effects can influence results in these types of tests, especially at very high strain rates. Additionally, intrinsic and extrinsic properties of the specimen affect inertial effects. Generally, smaller specimens, as well as low density and high stiffness materials, reduce error introduced from these inertial effects [37]. Clearly, a significant amount of optimization in the length, diameter, and material used in the experiments bars and samples must take place.

Nomenclature

σ = amplitude of stress pulse

$\dot{\varepsilon}$ = strain rate

ε = amplitude of strain

v = velocity

Ls = length of striker bar (projectile)

C = elastic wave speed of material

t = time

F = force

H_s = Original length of test specimen

A = cross-sectional area

E = Young's modulus

u = Displacement of the bar

$\dot{u}$ = Velocity or strain Pulse

I = Incident

T = Transmitted

R = Reflected

Mathematical Theory

With valid assumptions as explained previously, relatively simple mathematical formulae result in the desired stress and strain values of the specimen.

Beginning with the one-dimensional wave equation:

$$\frac{\partial^2 u}{dx^2} = \left(\frac{1}{c_{0B}^2}\right)\frac{\partial^2 u}{\partial t} \tag{4}$$

And the differential definition of strain:

$$\varepsilon = \frac{\partial u}{\partial x} \tag{5}$$

$$\varepsilon = f' + g' = \varepsilon_I + \varepsilon_R \tag{6}$$

We can solve for time derivatives of displacement in both the incident and transmission bars:

$$\frac{\partial u_I}{\partial t} = c_{0B}(-f' + g') = c_{0B}(-\varepsilon_I + \varepsilon_R) \tag{7}$$

$$u_t = h(x - c_{0B}t) \tag{8}$$

$$\frac{\partial u_T}{\partial t} = -c_{0B}\varepsilon_T \tag{9}$$

From here we can start to solve for strain rate in the specimen:

$$\dot{\varepsilon} = \frac{\dot{u}_I + \dot{u}_t}{H_s} \tag{10}$$

$$\dot{\varepsilon} = \left(\frac{c_{0B}}{H_s}\right)(-\varepsilon_I + \varepsilon_R + \varepsilon_T) \tag{11}$$

Here we introduce the force equations:

$$F_I = A_B E_B(\varepsilon_I + \varepsilon_R) \tag{12}$$

$$F_T = A_B E_B \varepsilon_T \tag{13}$$

Assuming stress and therefore force equilibrium allows further simplification of the strain rate equation:

$$F_I = F_R \tag{14}$$

$$\varepsilon_I + \varepsilon_R = \varepsilon_T \tag{15}$$

$$\dot{\varepsilon} = \frac{2c_{0B}\varepsilon_R}{H_s} \tag{16}$$

Assuming an incompressible specimen and therefore constant volume:

$$A_{s0}H_{s0} = A_sH_s \tag{17}$$

Finally, expressions for stress and strain in the specimen:

$$\sigma_s = \frac{A_B E_B \varepsilon_T}{A_{s0}} \tag{18}$$

$$\varepsilon_s(t) = \left(\frac{2c_{0B}}{H_{s0}}\right)\int^{t} \varepsilon_R\,(t)dt \tag{19}$$

2.2.D. Alternative Dynamic Stress Test Methods

While the standard Split Hopkinson Pressure Bar (SHPB) or Kolsky Bar is the classical technique used to determine the high strain rate mechanical responses of various materials ($10^2 - 10^3\ \frac{1}{s}$) it is important to discuss alternative methods that have been used to attain similar results [33].

Miniature Kolsky Bar

The miniature Kolsky bar is, at its root, precisely what its name implies; a miniaturized version of the aforementioned Kolsky / Split Hopkinson Pressure Bar setup. A 1.5 to 3 millimeter range is used in place of the standard 6 to 25 millimeter range for the diameters of the bars thereby rendering the conventional use of strain gages and a Wheatstone bridge system ineffective [33]. This constraint holds true for the use of a strain gage on all bars with diameters less than 6 millimeters. However, given the reduced geometry of the system one can measure the strain pulse using interferometric measurements deduced from the interference patterns generated by the combination of two waves of equivalent length across the gratings at the midpoint of the bar. One can then classify the waves as either constructive (light) or destructive (dark) from the phase difference between the two initial waves. Furthermore equipping a transverse displacement interferometer (TDI) and normal displacement interferometer (NDI) to the bars to measure the longitudinal displacement and motion respectively [33].

While a smaller geometry is beneficial in preventing dispersion effects as the pulse's rise time is shortened and a state of equilibrium can be reached quicker the miniaturized Kolsky bar method runs into altercations when a transmitter bar is used as well as it struggles to accurately measure transverse displacement oscillations.

Pressure-Shear Plate Method

Like most one-dimensional plane wave analysis methods, the Pressure-Shear Plate makes use of two parallel plates, one experiencing a known velocity traveling in linear motion and the other at rest. In this technique, there is a flyer plate and a target plate of the same material. Each of these plates is flat, parallel to one another, and inclined at the angle of approach of the flyer plate as demonstrated in figure 15 [36].

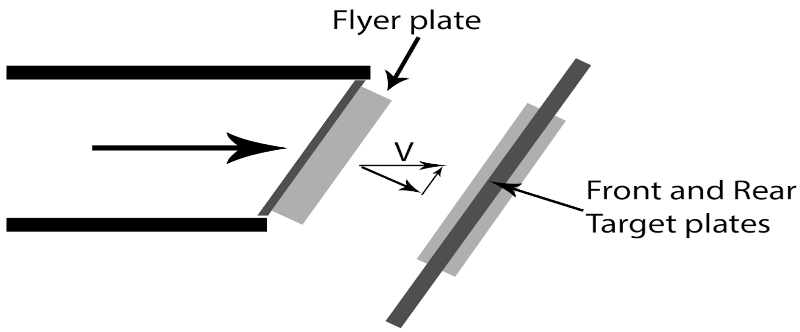


Figure 15. Depiction of a Pressure-Shear Plate Apparatus

Using a laser-interferometry technique comprised of a TDI and NDI configuration the elastic longitudinal wave speed and transverse wave propagating at the elastic shear speed can be measured and analyzed.

<u>Charpy / Izod Impact Test</u>

The Charpy / Izod Impact Test has a fairly different configuration for dynamic stress testing than those previously discussed. In the joint Charpy / Izod system, a weighted pendulum equipped with a striker is released downward from a known height towards the test specimen in a motion that will break off a piece of the specimen [29]. Individually, the impact tests are relatively the same except for the alignment of the test specimen with respect to the pendulum. The test specimen is aligned vertically with it fastened facing the pendulum during the Izod Impact Test whereas in the Charpy Impact Test the test specimen is aligned horizontally with it fastened facing away from the pendulum. The energy absorbed by the impact can be calculated using the initial height of the pendulum [29].

<u>Gardner Impact Test</u>

The Gardner Impact Test System has a simple yet reliable configuration. It features a variable mass impactor as its striker that is vertically released downward towards the test specimen. Using the relationship between the mass and initial height of the striker the energy of the impact can be determined for the test specimen [29]. Likewise, the impact force can also be determined using an accelerometer. Because of the system's configuration, it can be applied to various materials of different shapes, sizes, and orientations. The data collected is both precise and accurate for normal and oblique impacts, and the test specimen itself can be dropped in place of using a striker [29]. Even though the Gardner Impact Test can accommodate a wide variety of materials it has been primarily useful amongst various rubbers and plastics.

2.3. Methodology

The following objectives were developed after an initial analysis of the Split Hopkinson Pressure Bar (SHPB) designed in fulfillment of a major qualifying project (MQP) at Worcester Polytechnic Institute (WPI) in 2017. The SHPB apparatus being discussed features a single stage gas gun, a striker bar fitted with multiple sabots for accuracy, two sets of incident and transmission bars (Maraging 350 Steel & 7075-T651 Aluminum), and a Tektronix MDO 3024 oscilloscope for data acquisition. The entire apparatus is mounted on two 10 foot steel I-beams, bolted together for a total length of 20 feet, held up by 6 custom built steel legs with manually adjustable vibration resistant feet.

Our primary methods included:

1. Restoration of the SHPB Apparatus
2. Alignment
3. Calibration
4. Data Acquisition

2.3.A. Restoration of SHPB Apparatus

The WPI SHPB is housed in a lab in the basement floor of the Higgins Laboratories building on campus. The MQP team that designed and manufactured the apparatus used Rust-Oleum Professional Smoke Gray Gloss Enamel on both of the I-beams and the chamber of the single stage gas gun as a precautionary measure to rust. However, the rest of the assembly remained unprotected and as a result of its environmental conditions, rust began to form. During our preliminary examination of the assembly, we found that significant corrosion had formed on the exterior of the barrel and unpainted portion of the pressure chamber, as well as on the metal segment of the momentum trap.

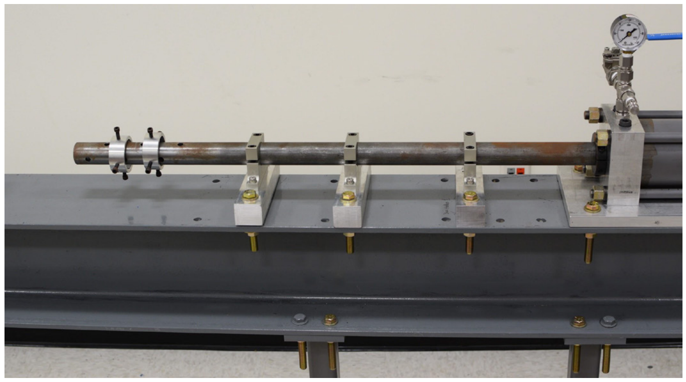


Figure 16. Sideway Visual of Corrosion on Gas Gun Barrel

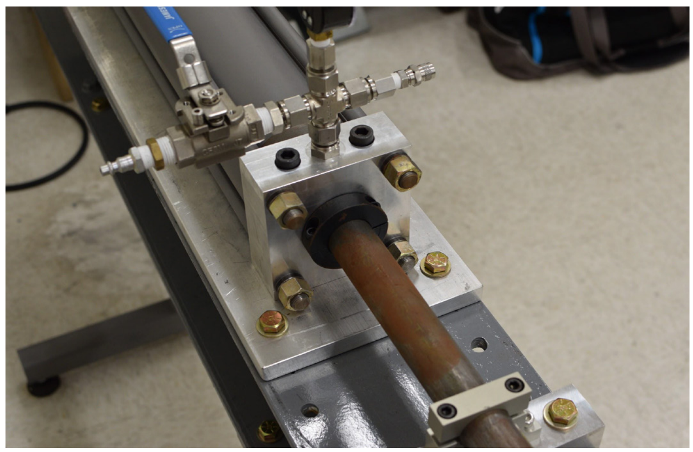


Figure 17. Top Visual of Corrosion on the Gas Gun Barrel

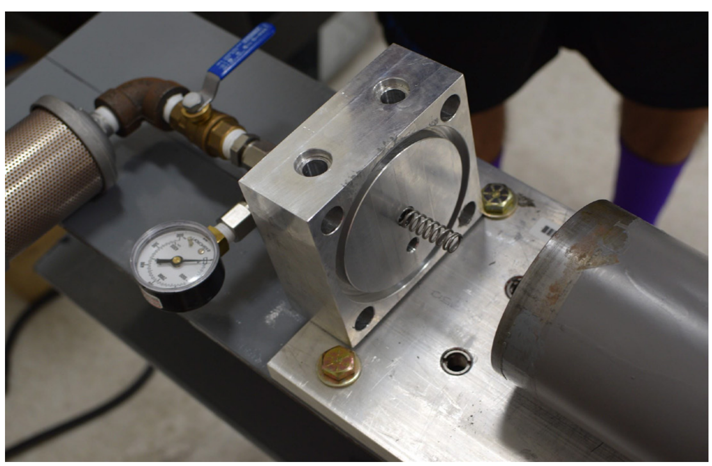


Figure 18. Visual of Corrosion on the Muffler Assembly and Gas Gun Chamber

While some parts of the apparatus are made from rust-resistant materials such as stainless steel and plated zinc yellow-chromate most of the apparatus is not. There are various ways to prevent corrosion of metals including but not limited to: applying a coating, Cathodic protection, corrosion inhibitors, or plating. A coating of paint or other organic substances such as Alkyd and epoxy ester, two-part urethane, acrylic and epoxy polymer radiation curable, and vinyl, acrylic, or styrene polymer combination can be applied to inhibit corrosion [25]. The same can be achieved by plating the parts either physically or hot dipping them in Tin, Chromium, Nickel, or Cobalt. Cathodic protection consists of introducing an electrolytic anode of some metal to be sacrificed in place of the cathode during the oxidation process [25]. Lastly, corrosion inhibitors are chemicals that react with the metal's surface and gases that cause oxidation to occur, thereby interfering with the process and preventing rust [25].

In ensuring the prevention of oxidation of the SHPB we can prolong the lifespan of the materials it is built out of as well as repeatability of experiments without fear of material failure.

2.3.B. Methods of Alignment

To uphold the mathematical theory behind the Split Hopkinson Pressure Bar, the apparatus must perform one-dimensionally otherwise the experimental analysis is null and void. To ensure single dimension functionality, one can employ a multitude of alignment options to the assembly. The apparatus used in the experiments mentioned later in this paper is mounted on two bonded I-beams with its legs having adjustable feet, the only adjustable alignment option available presently.

An optical table is preferable for aligning an SHPB system during construction as one can adjust the table until level and then secure the SHPB on top. Dual axis adjustable collars and a mounted alignment laser combination can be used when using alternative surfaces. One can also align the system by simply using a generic level and touch to see if the striker, incident, and transmission bars are all aligned with respect to each other. Alignment is a significant part of using the SHPB technique and making the process simple yet effective is of the utmost importance for repeatability of experiments.

2.3.C. Methods of Calibration

Once the SHPB is aligned one needs to perform a calibration test to determine if their apparatus is accurate and precise before progressing to dynamic stress testing of materials with unknown properties. The most common calibration techniques are bars apart, bars together, normal test with a well-documented flat test specimen, normal test with the same material using a non-flat test specimen, and offsetting the striker bar [31].

The bars apart and bars together tests measure the strain of the incident and transmission bars respectively by linearly firing the striker bar at the incident bar. Bars apart is, as it states, when the incident and transmission bars are not touching one another and the bars together is when both are coincident with one another.

The normal SHPB test with a known material consists of using the full apparatus to perform a dynamic stress experiment on a material that is well researched and documented. The material chosen for calibration of this device was 4340 steel, a material whose dynamic stress-strain response has been documented in literature. There are two variances of this technique using either a flat or non-flat test specimen of the same known material. The purpose behind a non-flat specimen is to intentionally record different results from your flat specimen experiments, typically off by a range of 3% to 8%, because if one is getting the same results, or differences are hidden within uncertainty, there is an error in your SHPB apparatus [31].

Lastly, one can test with the striker bar offset linearly from the incident bar by a known distance and perform a normal SHPB experiment. The results should be fairly similar to that of the normal SHPB calibration test mentioned previously but the test does require the individual to intentionally misalign the apparatus [31].

2.3.D. Methods of Data Acquisition

The SHPB being discussed, though manufactured as part of a previous MQP, began this project without means of data acquisition for dynamic stress testing. From Chapter 2 we recall that for one-dimensional wave analysis it is assumed that: one, stress wave propagation through the bars must be one-dimensional; two, the interfaces between bars and specimen must be planar; three, the specimen must be in stress equilibrium, following a brief 'ringing up' period; four, assume that the specimen is incompressible; five, frictional and inertial effects must be minimized to the point of negligibility. The SHPB utilizes two strain gages in a half-bridge Wheatstone bridge configuration to record the strain wave caused by the impact of the projectile on the incident bar. Two gages are mounted parallel with the bar in a half- bridge configuration while another pair is mounted off the bar to serve as balancing resistors. Generally, the more active gages in a bridge, the better readings are. However, as the compressive wave in the bar is unidirectional, all gages experience the same strain and therefore the same change in resistance, corresponding to their gage factor. This means a full-bridge of active gages would remain balanced throughout the experiment. Therefore, to prevent readings from individual gages from canceling the readings of the whole bridge, at most a half-bridge configuration can be implemented. As mentioned in chapter two of this paper some of the wave is absorbed by the test specimen, some is reflected back to the incident bar, and some is transmitted to the transmitter bar. However, since this wave occurs at such a minimal voltage an amplifier will be necessary to amplify the data to a readable level.

While having an existing Split Hopkinson Pressure Bar assembly is convenient; restoration, alignment, calibration, and data acquisition are all significant factors that must be taken into account before any dynamic stress experimentation can take place.

2.4. Apparatus Preparation and Experimentation

The restoration, alignment, calibration, and development of a data acquisition system for the Split Hopkinson Pressure Bar (SHPB) being discussed was satisfied over the course of three academic terms at the Worcester Polytechnic Institute (WPI), spanning roughly twenty-one weeks in total. Several guides were also developed to ensure repeatability and longevity of the apparatus for dynamic stress experimentation.

2.4.A. Restoration

A commercial corrosion inhibitor chemical was selected to both remove the present corrosion on the SHPB as well as prevent the apparatus from future corrosive occurrences. Specifically, a three-part Birchwood Casey gun bluing kit was used as it provides the thinnest layer of protection in comparison to other alternatives, such as paint, is inexpensive and user-friendly. In order to apply the bluing, the single stage gas gun was carefully dismantled using the procedures in Appendices C, D and E.

2.4.B. Alignment

To level the mounting surface of the SHPB, a composite of System 2000 Epoxy and 50% volume fraction fiberglass shreddings was used. Molds for the mounting plate of the gas gun and the collar mounting plates were designed and implemented to pour the epoxy mixture and hold it during the forty-eight-hour cure process. Once the mixture had cured, using a power sander and four-foot level, the epoxy mounts were sanded down until perfectly level with each other. Then the necessary holes for the mounting bolts were drilled and the mounting surfaces reconnected along with their respective daughter components. Once the gas gun and collars were mounted, the incident, transmission, and striker bars were put into place to determine the accuracy of the alignment through tactile and visual examination. Fine adjustments were made until alignment was satisfactory.

2.4.C. Calibration

In order to ensure the SHPB is working properly and assumptions are valid, two main tests are conducted, without a material sample present, before true experimentation can begin. The first of these is the bars together test. Strain measurements taken from the incident and transmission bar during one of these tests are displayed in figure 19.

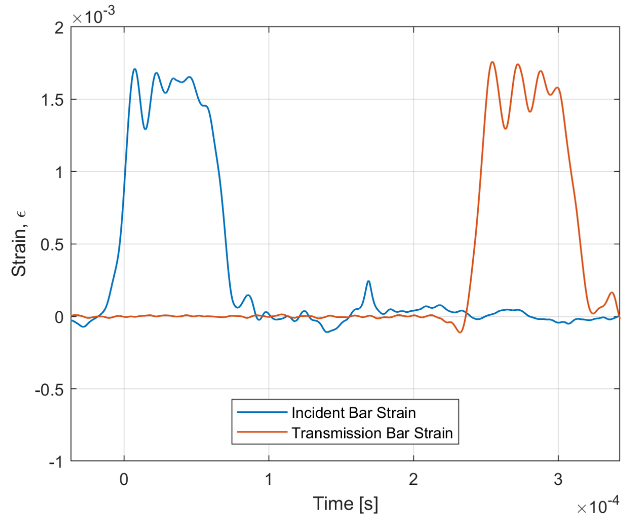


Figure 19. Bars Together Test with Low Pass Filter

During the bars together test, only two waves should be visible in the results, the incident and transmission. There should be no reflected wave if the apparatus is properly aligned. The large spike in the incident bar signal is a noise artifact which can be ignored if it does not interfere with the wave signal. If it does interfere, filtering and or outlier removal can reduce its disruption. Also note that the waves are of the same shape, magnitude, and length. This is an additional indication of good alignment, as well as minimal losses due to friction at the mounting interfaces. Essentially, the bars together test should appear as though the interface does not exist, and the strain gages are measuring the same wave as it appears along a single, longer bar.

The next of these tests is the bars apart test. This test should show three distinct waves, the incident, transmitted, and reflected, as in figure 20. This test shows less critical insight into the alignment of the system than the bars together test. From inspection, it is clear that although the incident and reflected waves are of approximately equal shape, magnitude, and length, the transmission wave does not share these characteristics. In a theoretical situation, this would not be the case, however, since the incident bar must travel forward in its mounts to make contact with the transmission bar, losses occur. It is important to note that in figure 20, the timescales for each wave are equal, however, the transmission wave signal was panned forward in time so that it could appear plotted against the first incident and reflected waves. In fact, the wave reverberated several times within the incident bar before making contact with the transmission bar. Such phenomena highlight the necessity of a momentum trap to prevent additional loading of the sample under experimental conditions.

The most important result of the bars apart test is an experimental measurement of the wave speed through the incident and transmission bar material. This property can be approximated using the density and bulk modulus of the material, but measuring it precisely and accurately yields better experimental data. This measurement is accomplished simply by measuring the distance from the strain gage to the end of the bar and the time between the incident and reflected waves. The wave speed is then determined to be twice this distance divided by the time between waves.

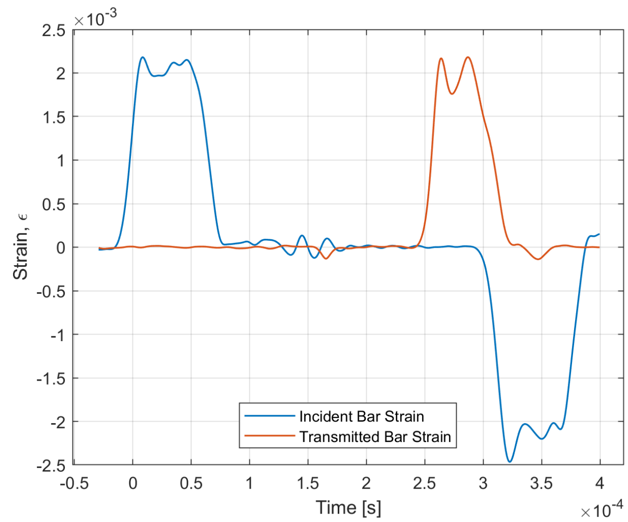


Figure 20. Bars Apart Test with Low Pass Filter

2.4.D. Data Acquisition

The data acquisition system is comprised of the Tektronix 3024 Oscilloscope, two half-bridge strain gage circuits, one on each the transmission and incident bars, two power supplies, and a MATLAB script for data analysis. For details on how to construct the half bridge circuit refer to Appendix F. Once the circuit is constructed it is time to apply the strain gages to the bars. Specific details on strain gage application can be found in Appendix F, G and H. Appendices I and J contain the steps to program the oscilloscope and how to perform the data analysis in MATLAB using the script in Appendix K.

2.4.E. Experimentation

Safety

When operating the Split Hopkinson Pressure Bar it cannot be stressed enough to operate in strict accordance with its safety policies and procedures as one is working with a high-velocity projectile that can cause harm if not fatal damage to the user. To ensure no risk occurs while preparing the SHPB for experimentation follow these four cardinal rules of safe operation:

1. DO NOT be a part of the firing path (i.e. in front of the barrel, between the gas gun and the incident bar, along the incident bar, in the test section (between the incident bar and transmission bar), along the transmission bar, and/or between the transmission bar and then momentum trap.

2. Ensure all fixed components (gas gun, bar mounts, blast box, momentum trap) are secured to the I-Beams BEFORE pressurizing the gas gun.
3. ALWAYS wear eye protection when there is pressure in the gas gun.
4. Ensure all personnel are aware and in a safe zone before loading and firing the gas gun.

Failure to abide by these four cardinal rules can result in serious injury and/or death. Do not play with the gas gun: it is not a toy. In addition to the four cardinal rules, the following are best practices for safe operation:

- Do not fire projectiles at the wall, they can and will cause damage.
- Do not fire a projectile without the proper momentum arresting system in place. Projectiles can rebound unexpectedly causing injury to personnel and/or damage to expensive, precision equipment.
- Perform a quick inventory check to make sure that none of the projectiles are loaded into the barrel of the gas gun.
- DO NOT under any circumstance look down the barrel until you are confident that there is no loaded striker AND the gun is depressurized.
- If there is a striker loaded in the barrel simply open the rear valve and slowly pressurize the gas gun (open the forward valve) to remove it.
- Similarly do not make any adjustments to the bar mounts, momentum trap, etc. until the gas gun is unloaded and depressurized.
- Make sure that the gas gun is not only disconnected from the air compressor but also depressurized by checking the forward gauge.
  - If connected to the air compressor, simply disconnect it from the gas gun by pulling the safety release and sliding it off the inlet.
- If the forward gage shows that there is pressure in the chamber using the forward valve to release the pressure. There will be some noise as the air is released through the male compressor fitting.
- Once the barrel is empty and the gas gun depressurized you are able to work on the SHPB i.e.:
  - Install/adjust the incident and transmission bars
  - Mount the strain gages to the bars
  - Adjust the momentum trap
  - Mount a test specimen
  - Or any other task

It is critical that any user of the SHPB understand the mechanics of how their apparatus operates and the risks that can occur from negligence.

<u>Performing an Experiment</u>

To perform an experiment using the SHPB:

1. Check that the gas gun is assembled, the strain gages are mounted, and the circuit is assembled and connected.
2. Connect the air compressor, close the forward valve, and turn on the compressor. Shut the compressor off when the pressure is 20 psi greater than the desired test pressure.
3. Turn on the oscilloscope. Check to ensure the desired test profile is loaded. Make sure a USB drive is inserted into the port on the backside.
4. Load the desired striker bar into the barrel of the gas gun. Use a generous amount of No. 105 Motor Assembly Grease on the exterior surfaces of the Delrin sabots. The incident bar may need to be temporarily removed to fit larger striker bars.
5. Check alignment between the striker and incident bars as well as the incident and transmission bars.
6. Open the forward valve until the forward gage reads 10 psi. This will ensure the gun is sealed and will not advance the striker bar before firing.
7. Using the black carbon fiber rod, slowly slide the striker bar down the barrel until the tape mark. Do not force the striker bar or exceed the distance of the tape to prevent accidental firing of the gun.
8. Place the sample between the incident and transmission bars. Use No. 105 Motor Assembly Grease on the flat faces of the sample and the pressure of the bars to hold it in place. Ensure the sample is as centered as possible.
9. Place the blast box around the test section.
10. Using a small amount of No. 105 Motor Assembly Grease, attach a new copper pulse shaper to the forward face of the incident bar. Ensure the pulse shaper is as centered as possible.
11. Open the forward valve until the forward gage reads the desired test psi.
12. On the oscilloscope, press the Run/Stop button (usually illuminated red) so the single button is illuminated green. This activates the window triggering for the experiment.
13. Perform a quick visual inspection to ensure all components are aligned and centered.
14. Ensure all personnel are aware a test is about to take place, and clear from the collision location, test section, and momentum trap.
15. Fire the gun by quickly opening the rear valve. Do not close the rear valve until all the pressure in the gas gun has dissipated. The oscilloscope should automatically measure the strain waves and save the data to the USB drive in .csv format.

<u>Data Analysis</u>

Once proper calibration and setup have been completed, tests can be conducted using the SHPB. In an effort to confirm our calibration we tested a material which had already been tested in literature, 4340 steel [30]. Three tests were conducted at varying gas gun pressures, 50PSI, 80PSI, and 100PSI, each using a copper pulse shaper. Each sample had approximate dimensions of 6.3mm diameter and 3.1mm length. More precise measurements were made for each individual experiment. Data from the test at 100PSI are presented below, beginning with the strain responses recorded in the incident and transmission bars.

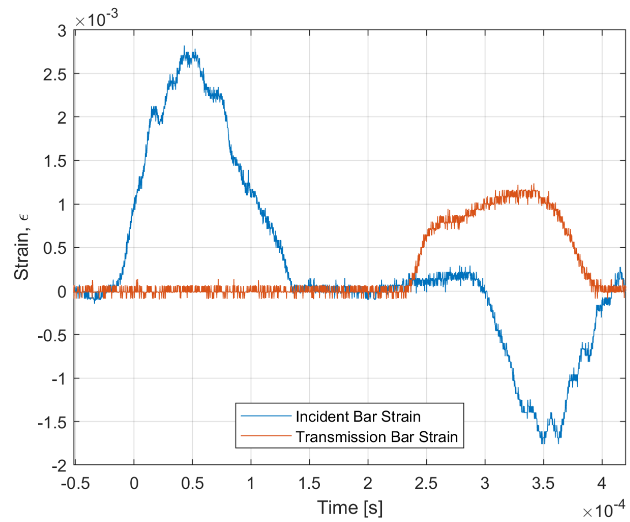


Figure 21. Strain Response in Bars, 4340 Steel, 1927 s^{-1} Strain Rate

Using the mathematical analysis explained previously, these strain measurements, along with certain known properties of the bars and physical dimensions of the sample, an engineering stress-strain curve for the sample is produced.

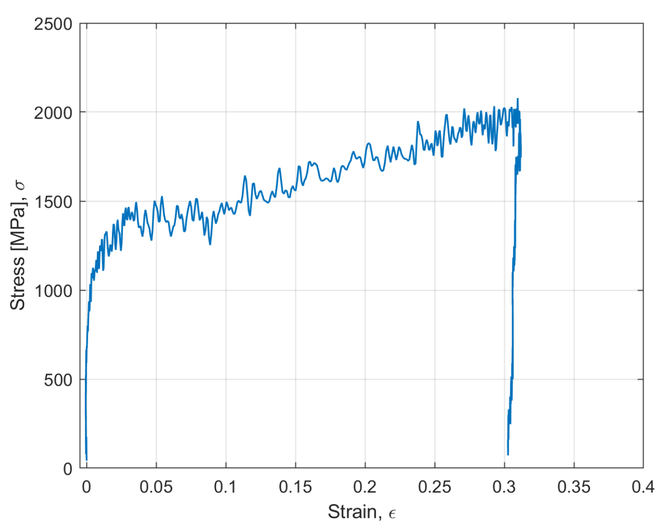


Figure 22. Engineering Stress-Strain Curve, 4340 Steel, 1927 s^{-1} Strain Rate

Using a bit more mathematical analysis, the engineering stress-strain curve can be converted to a true stress-strain curve.

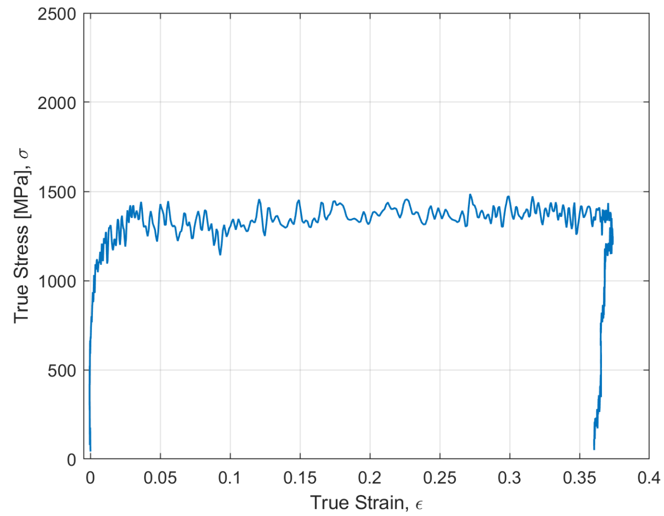


Figure 23. True Stress-Strain Curve, 4340 Steel, 1927 s^{-1} Strain Rate

In an effort to confirm the validity of our assumptions, we can calculate the stress at each interface of the sample. This is illustrated in figure 24. Apart from some dispersion oscillations, the specimen appears to be in relatively good stress equilibrium.

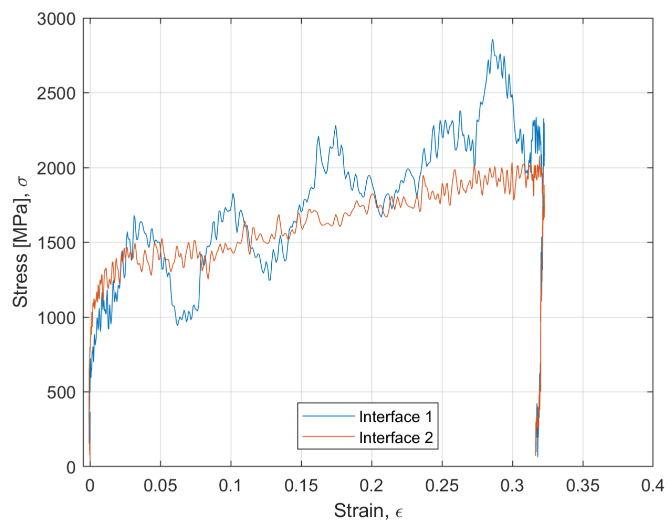


Figure 24. Interface Specific Stress-Strain Curves, 4340 Steel, 1927 s^{-1} Strain Rate

These signals do contain a fair amount of noise, this can be reduced by applying a low-pass filter to the data. The appropriate cutoff frequency was determined by examining the data in MATLAB using a fast Fourier transform. Accounting for at least a portion of this noise reveals significantly smoother stress-strain curves, as shown below.

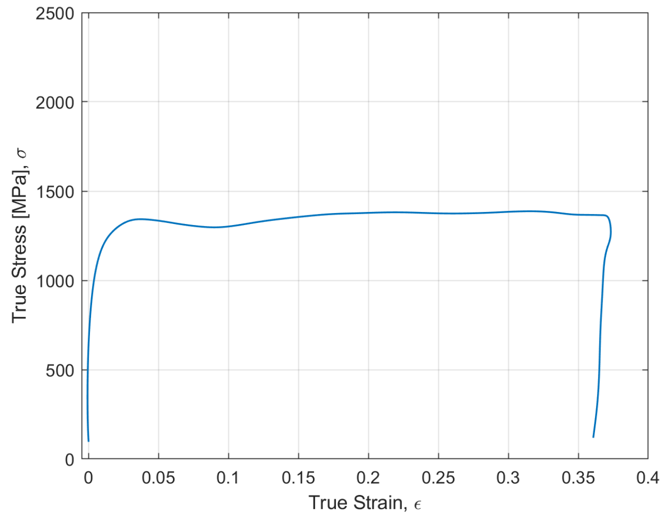


Figure 25. True Stress-Strain Curve, 4340 Steel, 1927 s-1 Strain Rate after Low Pass Filter

Aggregating the true stress-strain curves for each of the three tests together reveals the clear effect that varying strain rate has on material properties.

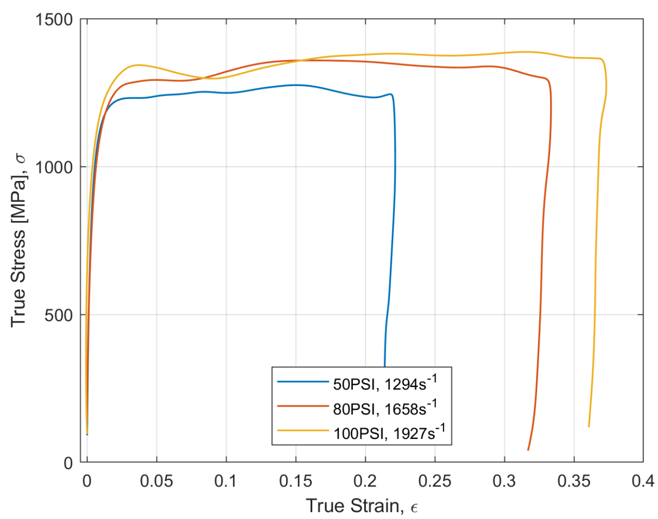


Figure 26. True Stress-Strain Curve, 4340 Steel, Varied Strain Rate, After Low-Pass Filter

Subsequently, the data we collected can be compared to data from previous tests on similar materials. The data we collected is compared against data collected by another group testing the same alloy at a similar strain rate.

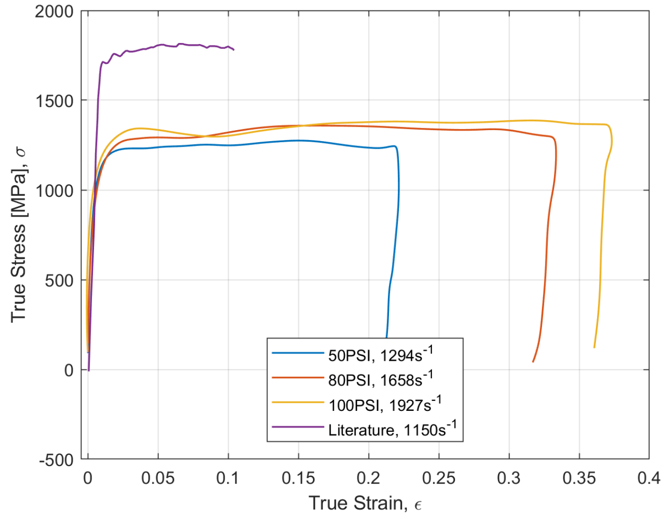


Figure 27. True Stress-Strain Curve, 4340 Steel, Varied Strain Rate, Compared to Literature

Evident by the significant mismatch in yield strength, especially between the most similar strain rate, our data does not match the magnitude of previously conducted experiments. The likely cause of this is due to varying hardening treatments of the alloys between experiments. The test conducted by Fret et. al. used the same 4340 steel alloy, but with a Rockwell hardness of C43, we used an alloy with a hardness of C25. This significant difference in hardness makes the two materials difficult to compare. The general shape of the curves follow a similar shape of linear elastic regions and plastic deformation, however, the magnitudes at which yield occurs and the amount of deformation incurred between the materials make the use of these results for calibration impossible.

2.5. Conclusion & Recommendations

This Major Qualifying Project has succeeded in restoring the Split Hopkinson Pressure Bar to an operational condition as well as implementing several improvements and capabilities. In its current state, the apparatus is now aligned to the highest degree of accuracy reasonably attainable through visual and tactile feedback, capable of extracting data from experiments, and performing these experiments in a repeatable manner.

Tests conducted on 4340 steel alloy at multiple high strain rates have confirmed that the SHPB is capable of delivering self-consistent results as well as demonstrated the effects of varying strain rates on this material. Comparison of tests performed on this device to those conducted by others has not yet been able to confirm the accuracy of this SHPB. This is due to variances in the processing of these alloy samples. Generally, it can be assumed that harder samples will demonstrate increased strength compared to softer samples of the same material. This phenomenon was confirmed during this project, as our specimen was of a lower Rockwell hardness than the specimen it was compared to. However, there is currently no definitive way of determining how much lower the strength of our alloy should have been. Additional testing of specimens with better-known properties is required to calibrate this difference.

The testing of additional materials for calibration purposes is the most important recommendation set forth for future improvement of this device. This will include both stiff materials for use with the steel incident and transmission bars, as well as more compliant materials for use with the aluminum bars. Additional improvements can also be made to the system by remachining certain components. The Delrin mounts which support the bars have channels engraved into them which prevent translation along the bar, in its current state, the tolerances of these channels are too tight and should be loosened. This will prevent the minor deformation of the mount and subsequent increase in friction of the bars. The Delrin sabots which support the striker bars also need to be altered so that they do not slide along the bar upon impact. Possible solutions to this issue include remachining with tighter tolerances or application of an adhesive. Finally, issues were encountered in this project regarding strain gages either liberating themselves from the bar or having their wire connections snap. We recommend connecting the gages to the amplifier circuit with thinner gauge wire than currently in use to remove some of its whiplash effects. Once this issue is resolved, balancing shunt resistors should be placed on the bar, perpendicular to the active gages, so that they help remove effects of non-uniform wave propagation.

At the conclusion of this Major Qualifying Project, the Split Hopkinson Pressure Bar is capable of being used to test metals in high strain rate experiments in a repeatable and self-consistent manner. Continued improvements of the device will further its capabilities in accuracy and range of testable materials.

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APPENDIX A. ACTUATION METHOD CASE STUDY

A tensile test necessitates a tensile force being applied to the sample. There are a large number of different possible actuation methods with various benefits and drawbacks that should be considered. Additionally, there is fatigue as a desired but not required functionality of the system, so the trade study can assist in determining if this functionality is attainable.

A.1. Alternatives

Car jack and power drill or hand crank

A jack was considered for this application because it is a manner in which people apply very high forces without the use of complicated machinery. This method was primarily considered because of its incredibly low cost. Assuming a power drill could be acquired/borrowed at zero cost, the only cost is approximately $50 for a reasonably priced car jack. As this system is primarily designed for raising cars to a particular height within perhaps a couple inches, the precision of both applied force and applied displacement will be very low [18].

Leveling Scissor Jack [18]

Heavy Duty Linear Actuator –[7]

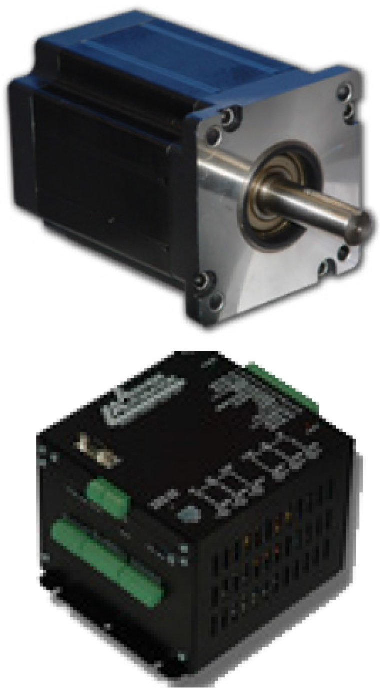
Linear actuator

It is possible to purchase linear actuators off-the-shelf, such as the Model PA-17 from Progressive Automations [7]. These systems have the benefit of being professionally fabricated but still reasonably inexpensive. However, they are difficult to impossible to customize/repair after purchase. Also, these standard actuators will be completely incapable of fatigue testing.

Stepper motor/lead screw combination

The current design uses an AA 42Y212S-LW8 stepper motor with driver from Anaheim Automation. This combines with a lead screw and nut to drive a crosshead, moving the sample.

Of all of the different configurations, this one is the most adaptable by a significant margin. There is a very wide variety of stepper motors and lead screws available, and changing the lead screw to get a different mechanical advantage/resolution could even be done after the system is constructed.



Stepper motor and programmable controller – [19]

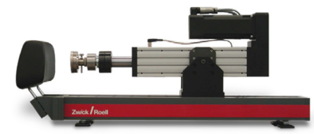
Ball screw and ball nut – [20]

Hydraulic actuation system

There are multiple options for a hydraulic actuation system. A discussion with MTS systems led to a ballpark system cost of greater than $100,000. TestResources recommended a complete system costing on the order of $85,000.

The reason for the high cost is because this would necessitate not just a hydraulic actuator, but also an entire hydraulic power system, including a pump, fluid storage, and valves/piping.

If there were a hydraulic system already available, as there is in some of the research labs on campus, then the additional cost to create this machine would be lower.



TestResources 910 Series Fatigue Test Machine

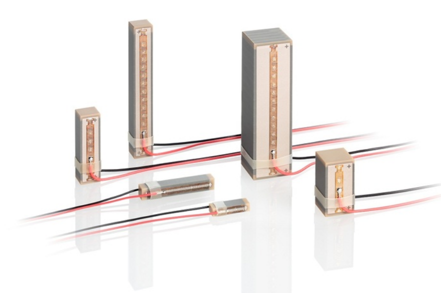
Zwick Electromechanical Actuator – [21]

Fatigue-rated linear actuator

Similar to the linear actuators, it is possible to purchase actuators rated for fatigue testing. There is a very significant price increase, however. The Zwick EZ010 Electromechanical Actuator for example, which meets our desired test specifications, costs $25,000 (with a built-in controller) [21].

Piezoelectric actuator

Piezoelectric actuators make use of piezoelectric materials (materials that deform when an electrical charge is applied to them). The actuators have properties drastically different from other actuation methods considered. The specific actuator being investigated is the P-888.91 stack multilayer piezo actuator from Physic Instrumente (PI). It has a resonant frequency of 40kHz, three orders of magnitude higher than is necessary for a fatigue application. However, The maximum travel range is only 38μm, meaning these actuators would not be capable of conducting tensile tests. They are being considered in this trade study solely because of the fantastic fatigue actuation properties [22].



Piezoelectric motor stack – [22]

A.2. Selection Criteria

Selection Criteria	Assigned Weight
Cost	4
Actuation force	2
Accuracy of applied force	3
Actuation distance	2
Fatigue capability	2
Lifespan / durability	2
Ease of use	1
Ease of Installation	1

Cost

At this point in the design stage, the budget is "keep costs relatively low" \$5,000 for the complete system is a plausible range. Cheaper is nicer, more expensive is potentially possible. Anything with a cost of over \$15,000 will be considered too expensive and therefore completely unsuitable for this application.

Cost is assigned a weight of **4** as one of the most important factors in this design

Cost will be assigned a score ranging from 0-4 using the formula:

$$score = \frac{\$10{,}000 - cost}{2500}$$

Costs greater than \$10,000 will be assigned a score of 0. Costs greater than \$15,000 will be an immediate failure of the component.

Actuation force

Actuation force is simply the maximum amount of force that the actuation method is capable of applying to the sample. As was calculated earlier, the desired force rating of the tester is 7.5kN. Actuation force is assigned a weight of **3** as without the ability to apply enough force, significant compromise will need to be made with the size and strength of the samples that the system is able to test.

Actuation Force Score Assignment

	Completely unsuitable	Below spec	Slightly below spec	Meets Spec.	Margin of safety	Exceeds spec.

Force	<5kN	5kN-6.5kN	6.5kN-7.5kN	7.5kN-8.5kN	8.5kN-10kN	>10kN
Assigned score	fail	0	1	2	3	4

Accuracy of applied force

This value refers to the precision with which a force can be applied to the sample; the smallest effective step size. This can be measured either using force or using displacement. That said, accuracy significantly exceeding the capability of the load cell to measure accurately serves no significant purpose.

Force accuracy is equated to displacement accuracy using the stated assumptions of a 10mm x 1 mm sample cross-section, a 5cm sample length, and a modulus of 750 MPa.

Because the accuracy of the force applied is important to the ability to run good tensile tests, force accuracy is assigned a weight of **3**.

Force Accuracy Score Assignment

	Not accurate	Significantly below load cell accuracy	Slightly below load cell accuracy	Matches load cell accuracy	Exceeds load cell accuracy
Force Accuracy	>200N	200N-50N	50N-10N	10N-2N	<2N
Displacement Accuracy	>1.33mm	1.33mm-333µm	333µm-67µm	67µm-13µm	<13µm
Assigned score	0	1	2	3	4

Actuation distance

Actuation distance is the effective range of motion of the actuator when moving the sample.

Due to the very high stiffness of CFRP, the expected actuation distance to fracture a 5cm sample is The desired actuation distance is 20cm. This larger distance also allows more flexibility in designing the structure of the tensile tester. Additional potential actuation distance confers no additional benefit because a larger test frame would be necessary to gain the benefit.

Because actuation distance can be worked around for the most part but would be nice to have, it is assigned a weight of **2**.

Actuation Distance Score Assignment

	Insufficient				
Distance	<1cm	1cm-2cm	2cm-5cm	5cm-10cm	10cm-20cm
Assigned score	0	1	2	3	4

Fatigue capability

It is desired that the system is able to fatigue composites to failure. The desired level of fatigue is 30Hz, but slower fatigue rates would still be useful.

As this is an optional functionality, fatigue capability is assigned a weight of **2**.

Fatigue Capability Score Assignment

	Not capable of fatigue	Can do fatigue slowly without failing	Capable of some fatigue	Capable of "good enough" fatigue	Capable of desired fatigue
Force	-	.5Hz-5Hz	5Hz-15Hz	15Hz-30Hz	>30Hz
Assigned score	0	1	2	3	4

Lifespan / durability

This category is somewhat speculative but important to consider. It refers to the likelihood of failure of the actuator. Because of the setups we are using, this is very difficult, if not impossible to even estimate, this selection criterion is addressed with a rubric.

Because system lifespan is important but less important than a functioning system, lifespan/durability is assigned a weight of **2**

Lifespan/durability Score Assignment

	Parts used outside of	Student fabricated; some parts	Professionally manufactured;	Student fabricated;	Professionally manufactured;

	rated specifications	used other than designed	used other than designed	all parts used as designed	used as designed
Assigned score	0	1	2	3	4

Ease of use

This is both a subjective and a speculative category but is useful nonetheless. It includes factors such as time needed to set up the machine for tests, time to switch out components if necessary, and number of components to maintain

Because the system will be used by untrained undergraduate students, ease of use is assigned a weight of **3**

Ease of Use Score Assignment

	Actuator requires large support system and significant time investment to operate	Actuator requires large support system or significant time investment to operate	Actuator requires moderate time investment and/or support system to operate	Actuator requires slight time investment or small support system to operate	Actuator simply works
Assigned score	0	1	2	3	4

Ease of assembly

Ease of assembly is a simple measure of how much effort must be invested to add the actuator to the overall system. If time is saved in this step, the team will be able to spend time on other aspects of the project.

Because the team has limited time but could devote resources to constructing an actuator, ease of assembly is assigned a weight of **2**.

Ease of Assembly Score Assignment

	Actuator must be constructed, interfaces require machining	Actuator must be constructed, interfaces require no machining	Actuator fully constructed, interfaces require machining	Actuator fully constructed, interfaces require no machining	Full system is preconstructed
Assigned score	0	1	2	3	4

A.3. Scoring Alternatives

Car jack and power drill or hand crank

Criteria	Value	Weight	Assigned Score	Comment
Cost	\$50	4	4	
Actuation force	~ 22kN	3	4	
Accuracy of applied force	~ ±25%	3	0	Force will be applied by a setting on a power drill. It will not be accurate.
Actuation distance	50cm	2	4	
Fatigue capability	none	2	0	
Lifespan / durability	Professionally manufactured; used other than designed	2	2	A car jack is not designed to be used for tensile testing and could likely fail due to misuse
Ease of use	Large time investment	3	1	Motor must be powered by handheld drill. Speed/power directly controlled by user
Ease of assembly	Fully constructed; no machining	2	3	
Weighted Total	49			

Linear actuator

Criteria	Value	Weight	Assigned Score	Comment
Cost	$450	4	3.8	Cost includes actuator and driver
Actuation force	8.9kN	3	3	
Accuracy of applied force	500µm	3	1	This is the accuracy that can be read by the built-in potentiometer. Greater accuracy could be possible by integrating load cell feedback.
Actuation distance	20cm	2	4	
Fatigue capability	Not capable of fatigue	2	0	
Lifespan / durability	Professionally manufactured; used as designed	2	4	
Ease of use	Small support system; feedback from potentiometer/load cell	3	3	
Ease of assembly	Fully constructed; no machining	2	3	
Weighted Total	58.5			

Stepper motor/lead screw combination

Criteria	Value	Weight	Assigned Score	Comment
Cost	$1200	4	3.5	Cost includes stepper motor, driver, and lead screw
Actuation force	10kN	3	4	

Accuracy of applied force	10µm	3	4	Depends heavily on lead screw. Stepper motor is accurate to 1.8°. Using pitch of 2mm for lead screw.
Actuation distance	20cm	2	4	Any distance can realistically be achieved
Fatigue capability	Not capable of fatigue	2	0	
Lifespan / durability	Student fabricated; all parts used as designed	2	3	
Ease of use	Moderate time investment	3	2	
Ease of assembly	Actuator must be constructed; requires machining	2	0	
Weighted Total	58			

Hydraulic actuation system

Criteria	Value	Weight	Assigned Score	Comment
Cost	~$85,000	4	fail	Price is for a full system
Actuation force	10kN	3	4	
Accuracy of applied force	?	3	?	Data not pursued because of price
Actuation distance	20cm	2	4	
Fatigue capability	15Hz	2	3	

Lifespan / durability	Professionally manufactured; used as designed	2	4	
Ease of use	Hydraulic support system required	3	1	
Ease of assembly	Full system preconstructed	2	4	
Weighted Total	fail			

Fatigue-rated linear actuator

Criteria	Value	Weight	Assigned Score	Comment
Cost	$25,000	4	fail	
Actuation force	10kN	3	4	
Accuracy of applied force	2.1nm	3	4	
Actuation distance	20cm	2	4	
Fatigue capability	15Hz	2	3	
Lifespan / durability	Professionally manufactured; used as designed	2	4	
Ease of use	No support system, built in measurement/control system	3	4	
Ease of assembly	Fully constructed; no machining	2	3	
Weighted Total	fail			

Piezoelectric actuator

Criteria	Value	Weight	Assigned Score	Comment
Cost	\$2000	4	3.2	Includes actuator and amplifier
Actuation force	3.2kN	3	fail	
Accuracy of applied force	<1nm	3	4	Better load cell needed to really take advantage of sub-nanometer resolution
Actuation distance	32µm	2	0	Absolutely tiny actuation distance. Would not fracture any but the stiffest of samples.
Fatigue capability	40kHz	2	4	
Lifespan / durability	Professionally manufactured; used as designed	2	4	
Ease of use	Amplifier necessary	3	3	
Ease of assembly	Fully constructed; machining required	2	2	
Weighted Total	fail			

Summary

Actuation method	Assigned Score
Car Jack	49
Linear actuator	58.5
Stepper motor/lead screw	58
Hydraulic actuation	Fail; too expensive
Fatigue-rated linear actuator	Fail; too expensive
Piezoelectric actuator	Fail; insufficient force and travel

A.4. Reflection

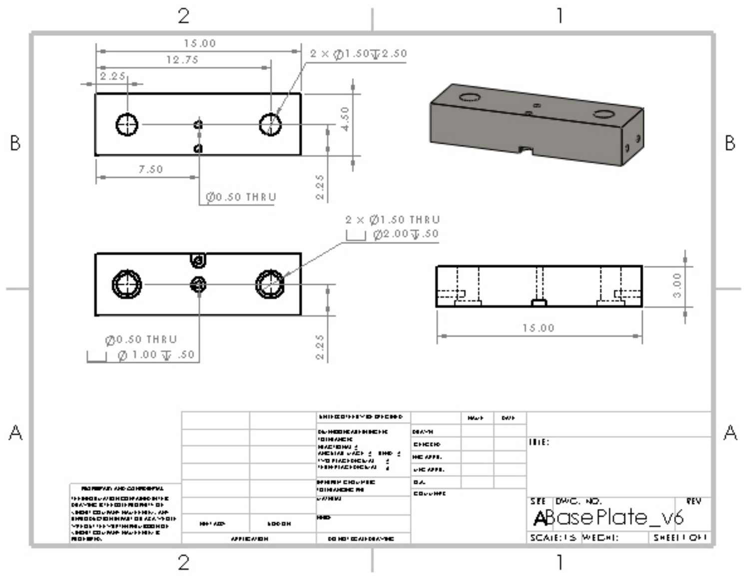
Based on the results of the trade study, it appears that the linear actuator is the best choice for the project. One important consideration is the accuracy of the applied force. Further study is needed if the accuracy of the applied force can be improved for the linear actuator by use of a feedback system with the load cell. This could potentially increase the score of the linear actuator enough to surpass the stepper motor/lead screw combination.

It should be noted that while the hydraulic and fatigue-rated actuators are too expensive to be considered for this project, they are included in this trade study as potentially useful information to any future group designing a similar system, perhaps with more generous budgetary constraints.

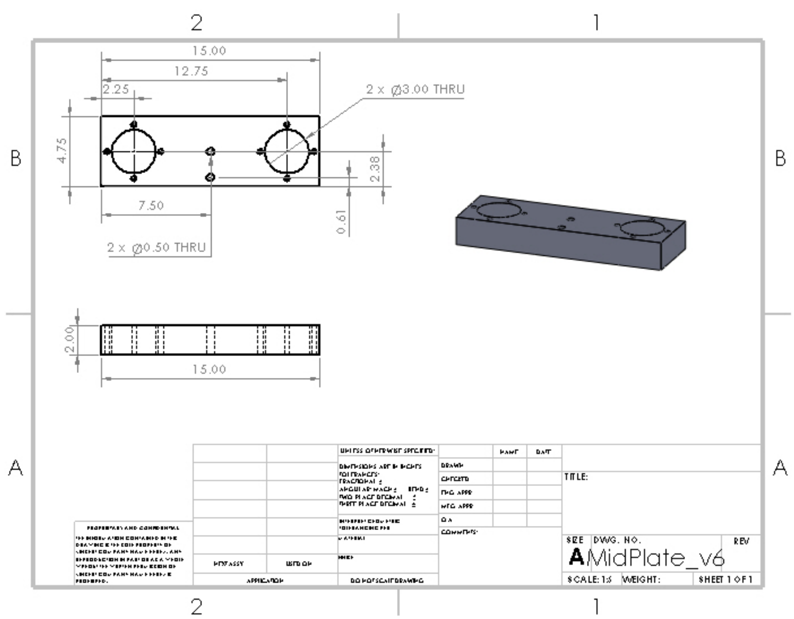
The piezoelectric actuator is not capable of the actuation distance necessary for fatigue testing, nor the necessary force. *However*, it appears to be an excellent for fatigue testing, at prices significantly lower than any other fatigue-capable option. In fact, it appears it would likely be significantly cheaper to create two separate machines (or a single machine with multiple actuators) than it would be to use one of the actuation systems capable of both operations. Note that this naturally would significantly increase design and assembly complexity.

APPENDIX B. DESIGN AND ANALYSIS

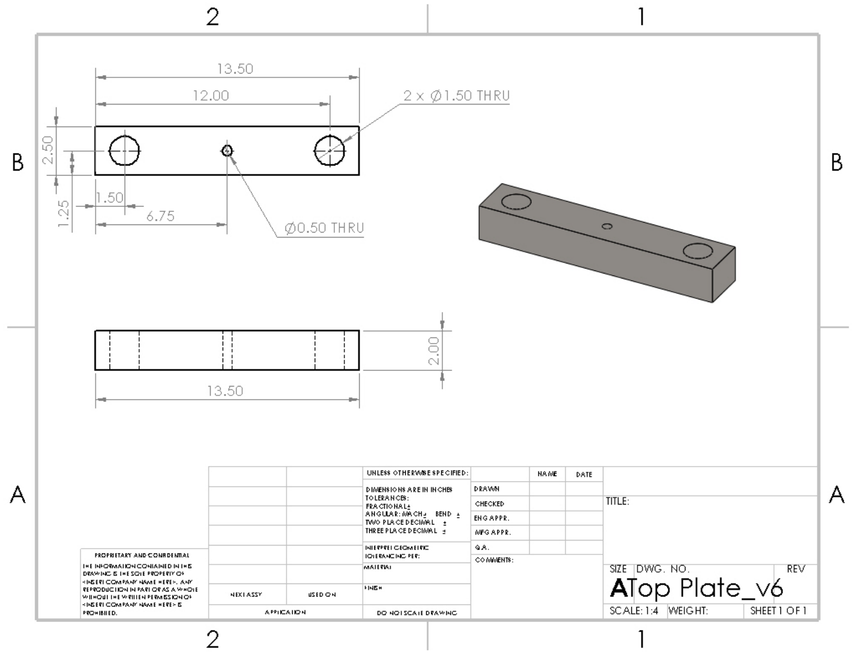
B.1. Structural Frame



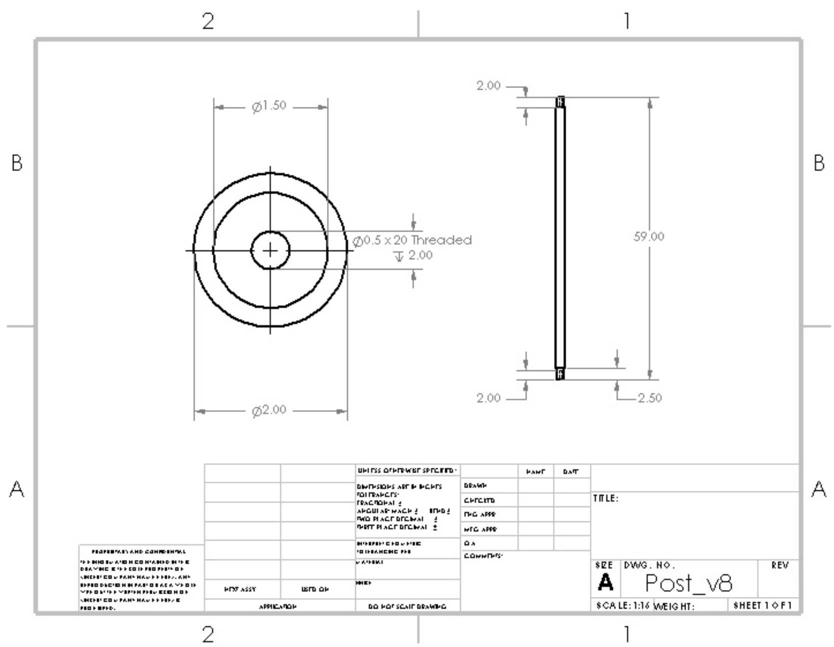
Base Plate



Mid-Plate

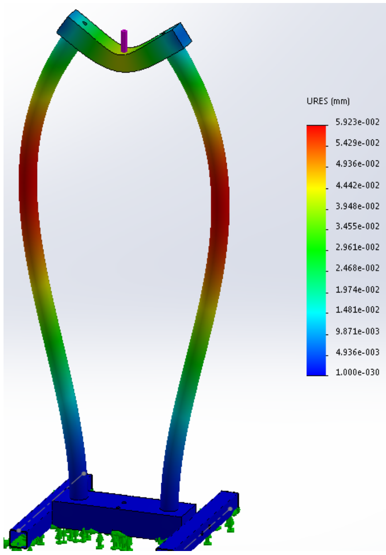


Top Plate

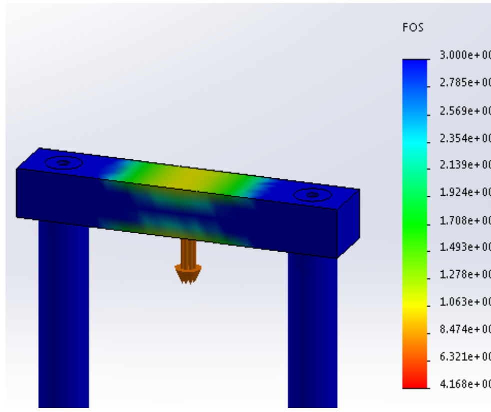


Support Post

B.2. Structural Frame Analysis



Deflection Test of Structural Frame



Static Factor of Safety Test of Structural Frame

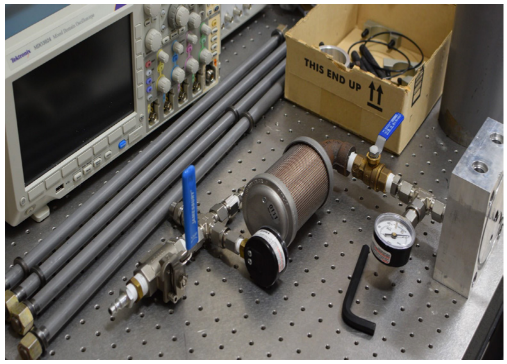
Study name:Test Frame Buckling

Mode No.	Buckling Factor of Safety
1	17.366

Buckling Factor of Safety Test of Structural Frame

APPENDIX C. DISMANTLING THE GAS GUN:

1. Ensure the gas gun is depressurized by disconnecting the air compressor and opening the forward valve.
2. Remove the forward valve/gage/regulator plumbing by unscrewing (turn counterclockwise) the fitting from the forward aluminum end cap.

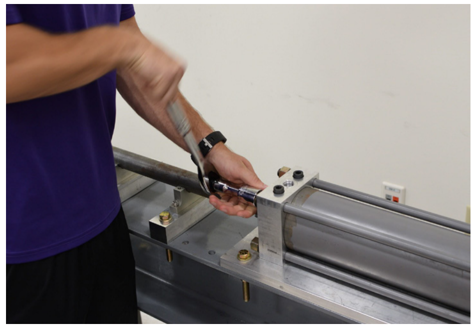


Disconnected Muffler and Fill Assemblies

3. Remove the (4) 9 mm inch hex head screws from the aluminum end caps. The gas gun is now free from the mounting plate.

Removal of Hex Screw from Gas Gun End Caps

4. Remove the rear valve/gage/muffler plumbing by unscrewing (turn counterclockwise) the fitting from the rear aluminum end cap.
5. Using both torque wrenches, remove the 8 ⅝-18 mm nuts from both ends of the retaining rods. Loosen these nuts in an even manner to prevent damage to the internal O-rings.

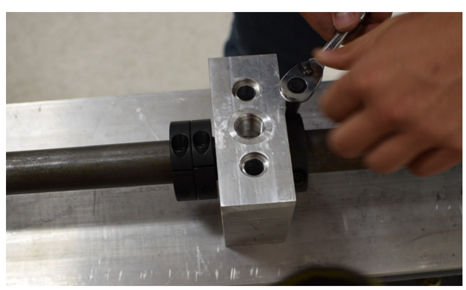


Removal of Retaining Rod

6. Remove the end caps from the chamber. Be careful not to scratch the inside of the chamber with the internal end of the barrel.
7. Remove the internal components by pushing them axially through the chamber. Use your hand or a soft object to prevent scratches on the chamber and components.

Visual of Internal Components inside Chamber

8. Remove the internal end of the barrel by unscrewing (turn counterclockwise).
9. Remove the retaining rings from the barrel and slide it out of the forward end cap.
10. Remove all o-rings from the forward and rear end caps and the internal end of the barrel.



Removal of Retaining Collar from the Barrel of the Gas Gun

11. Disassemble the internal components by removing the aluminum cap and the $\frac{5}{8}$-18 mm nut, sliding the steel rod and polycarbonate disk out of the Delrin aligner, and removing the $\frac{5}{8}$-16 mm nut to slide out the steel rod.

APPENDIX D. CLEANING THE GAS GUN

1. Use WD-40 and a paper towel to thoroughly remove dust, rust, and any other foreign contaminants from all metal surfaces, especially the inside of the barrel and the inside of the chamber.

Rust Removal Using Sand Paper

2. If the blued finish has been scratched off, refer to a bluing kit on the cleaning and bluing procedure.

Application of Gun Blu to Barrel

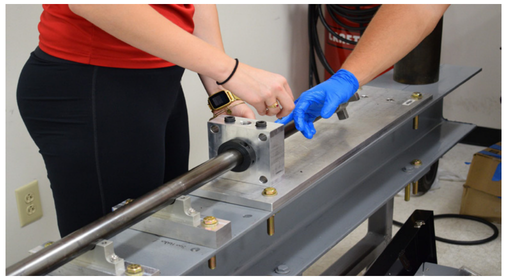
3. Wash off the plastic and aluminum components with water. Dry thoroughly before reassembly or storage.

Post Bluing Application Rinse with Water

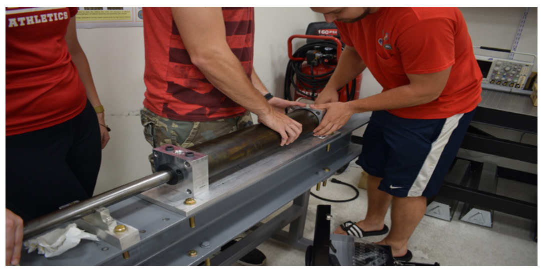
4. Lubricate all metal surfaces to preserve the components and prevent rust.

APPENDIX E. ASSEMBLING THE GAS GUN

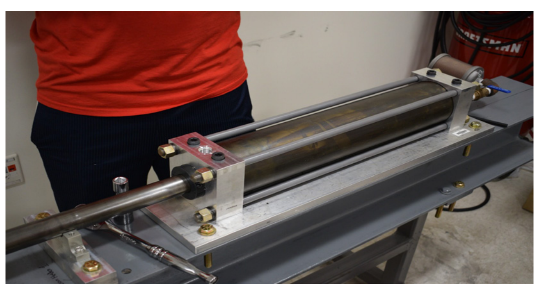
1. Assemble the internal components. Slide the steel rod through the polycarbonate disk so the lip on the rod is flush against the internal lip in the hole. Slide the ⅜-16 mm nut down the steel shaft and tighten until the polycarbonate disk is secure. Slide the steel rod through the Delrin aligner and thread the ⅝-16 mm nut on to the end of the threading. Screw the aluminum cap on and secure using the ⅝-16 mm nut.
2. Install the #220 O-rings in the barrel hole in the forward aluminum end cap.
3. Using lubrication, slide the barrel through the barrel hole. Note: the threaded end of the barrel must be on the same side as the #220 O-ring groove.
4. Press a #242 O-ring into the internal barrel end. Install the internal barrel end on the threaded end of the barrel. When the end cap is attached, the internal barrel end should be 13 inches from the inside of the forward end cap.
5. Install the retaining rings on the barrel. Start with the first internal retaining ring: ensure it is flush against the inside of the forward end cap and completely tighten. Repeat with the external retaining ring followed by the secondary internal retaining ring.
6. Lubricate the steel rod and the edge of the polycarbonate disk using No. 105 Motor Assembly Grease. Install the internal components by sliding the internal assembly (more specifically, the Delrin aligner) into the pressure chamber. Leave 1 inch of clearance from the rear end of the polycarbonate disk and the rear edge of the chamber.
7. Place a #242 O-ring into the groove on the forward and rear end caps.
8. Using at least two people, slide the chamber into the groove on the forward end cap. Be careful not to scrape the interior of the chamber with the internal barrel end. Place the rear end cap on the rear of the chamber. Ensure the countersunk holes of the end caps are oriented the same way. Slide the 4 retaining rods through the 4 holes in the end caps. Place a washer over each end, then hand tighten the 8 ⅝-18 mm nuts onto each end. Once all 4 rods are installed, tighten along each diagonal to 10 ft*lbs of torque using the torque wrenches.
9. Install the rear valve/gage/muffler plumbing by screwing the fitting into the rear end cap.
10. Secure the gas gun to the base plate with the (4) 9 mm hex head screws.
11. Install the forward valve/gage/regulator by screwing the fitting into the forward end cap.
12. Attach the air compressor to the gas gun. When the compressor stops, open the forward valve to pressurize the gas gun to 50 psi, then close the forward valve and listen for leaks.
13. To fire the gas gun, quickly open the rear valve. To depressurize the gas gun without firing, disconnect the air compressor and open the forward valve.



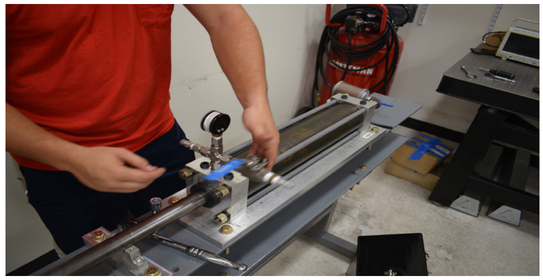
Securing the Barrel to the Forward Aluminum End Cap



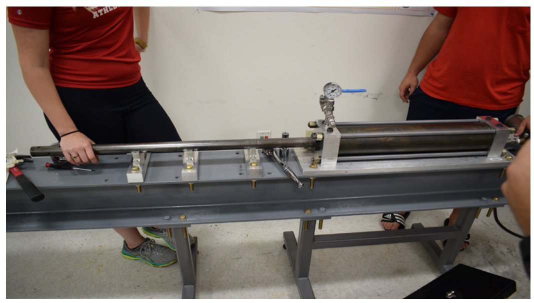
Sliding the Chamber and Securing with Rear Aluminum End Cap



Visual of Secured Muffler Assembly



Visual of Secured Fill Assembly

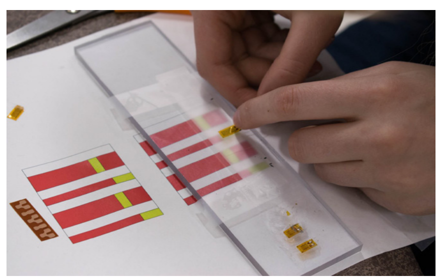


Fully Assembled Gas Gun

APPENDIX F. STRAIN GAGE APPLICATION

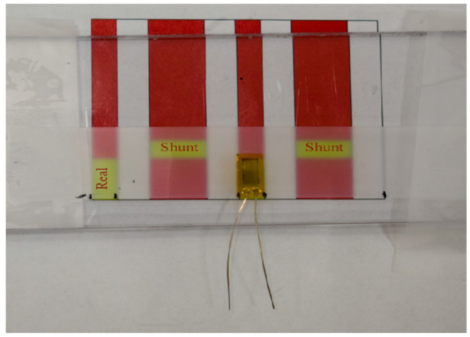
What you will need:

- Strain gage template provided in Appendix G
  - If doing shunt resistors on bar use green blocks that are labeled shunt
  - If doing recording strain gages on bar use green blocks that are labeled real
- A flat clear piece of material (acrylic or polycarb works well, and will be referred to as acrylic for the remainder of this guide)
- Gorilla Impact Resistant Glue
- Cellophane tape
- Razor blade or Xacto knife
- Omega Strain Gages
- Fine tip sharpie
- Jumper pads
- Soldering Iron
- Solder
- Electrical Tape



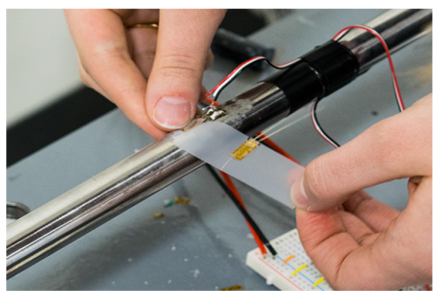
Application of Strain Gage using Template

1. Lay acrylic on the top of the template
2. Cut a large piece of cellophane tape (about an inch longer than the template)
3. Place the sticky side of the tape up on the acrylic and tape down ends so the tape with the sticky side up cannot move
4. Line tape edge up straight with the template bottom line
5. Take a sharpie and mark the end of the template and where edges of green blocks are
6. Line the strain gage up with the green blocks making sure the soldered side is the side touching the sticky side of the tape as shown below



Shunt and Strain Gage Location

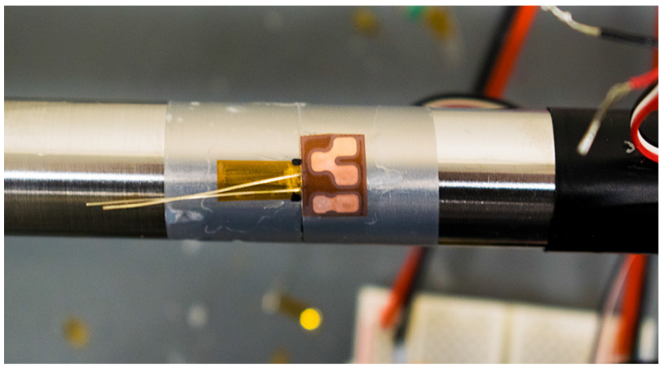
7. Place a small amount of superglue on the strain gage (just enough to adhere it to the bar securely)
8. Use the razor blade or Xacto knife to cut the tape where it is taped down (ideally you will have extra tape on either side of the marks that delineate the edge of the template)
9. Carefully line up the tape so it evenly wraps around the bar and pull it tight so there are no air bubbles



Mounting Strain Gage to Bar

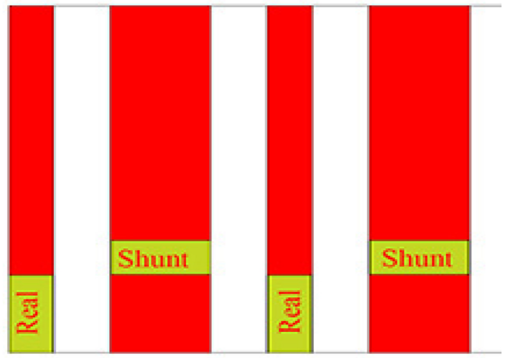
10. For best results let the superglue sit for at least 10 minutes so it fully cures
11. While waiting for the superglue adhering the strain to dry, begin attaching the jumper pads
12. Select the size jumper pad you would like to use and put superglue on the side that does not have the solder pads
13. Carefully place these at the edge of the strain gage where the wires are (the jumper pad's edge should be flush with the strain gages so the wires do not accidentally touch the bar causing a short)
14. Tape these down securely with cellophane tape so they do not slide while the superglue is drying
15. Once the superglue is dry carefully remove the tape from the jumper pads and the strain gages
16. Carefully trim the Omega lead wires so they are long enough to reach the jumper pads, but not so long that they leave the jumper pads

17. Tin the wires that will connect the jumper pads to the breadboard
18. Add solder to the jumper pads
19. Heat solder on jumper pads up and use tweezers to place Omega lead wires in
20. Heat solder again and insert the connecting wires so now both the Omega lead wires and the breadboard connecting wires are soldered onto the jump pad
21. Make sure there is a loop of wire so if the wire is tugged it does not pull on the solder pad
22. Tape wire to bar using electrical tape



Mounting the Solder Pad to the Bar

APPENDIX G. STRAIN GAGE TEMPLATE



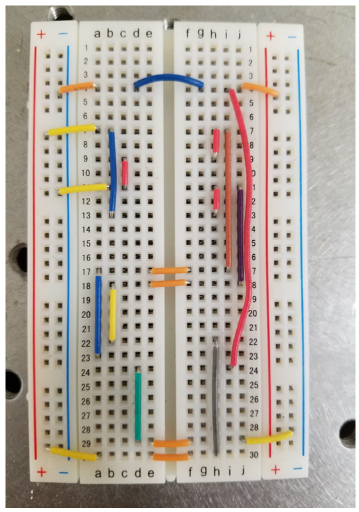
Strain Gage Template

APPENDIX H. CIRCUIT FOR STRAIN MEASUREMENT

You will need:

- Breadboard
- Wire
- Texas Instruments INA 128P Op-Amp
- Gain Resistor (Op-Amp gain = 1 + ($\frac{50\ k\Omega}{Resistor\ Value}$) we used an Op-Amp gain of 51 so a 1 kΩ resistor)

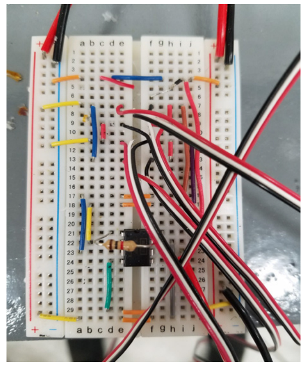
1. Follow the wiring diagram below:



Half-Bridge Circuit Wiring Diagram

2. Place the Op-Amp in rows 21-24 columns e and f making sure the indent is pointing towards the top of the breadboard (where the number 1 row is)
3. Place one wire of the selected gain resistor in row 21 column d
4. Place other wire of selected gain resistor in row 21 column g
5. Place shunt resistor wires in row 7 columns e and f
6. Place real resistor wires in row 9 columns e and f
7. Place shunt resistor wires in row 11 columns e and f
8. Place real resistor wires in row 13 columns e and f
9. Place power supplies such that the left negative terminal and right positive terminal are both connected to ground (connected across row 4) and the left positive terminal is biased positive 5 volts to this circuit common while the right negative terminal is biased negative 5 volts.

10. Place oscilloscope channel wire positive terminal in row 23 column i, the output of the amplifier, and ground the negative terminal, in the right side positive terminal in this case.
11. The final circuit should look like this:



Half-Bridge Circuit with Connected Power and Strain Gage Wires

APPENDIX I. OSCILLOSCOPE PROGRAMMING

1. Turn on the oscilloscope and insert a USB drive into the back of the scope.
2. Attach BNC connectors to measure excitation voltages and output voltages from the power supplies and amplifiers for each bar. In this experiment channel 1 was transmission bar output, channel 2 was incident bar output, channel 3 was transmission bar excitation, and channel 4 was incident bar excitation.
3. Adjust the scale of each channel so that the outputs so that the outputs measure on the scale of 500mV and the excitations measure on the scale of 1V.
4. Adjust the timescale to 200 microseconds. At the oscilloscopes sample length of 10,000 samples, this means a sample rate of 5 million samples per second.
5. Use the trigger menu to set the scope to trigger on the incident bar channel. The incident wave in our configuration is a negative voltage so set the trigger level to approximately 100mV below the unstrained output.
6. Under the test menu, set the scope to act on the event of a trigger. Set it to stop acquisition, save waveform to file, and save screen image.

APPENDIX J. ANALYSIS OF DYNAMIC DATA IN MATLAB

1. Open the MATLAB script provided in Appendix K. Ensure that the program is running in the same folder as the raw data is stored.
2. Ensure that all constants and hardcoded inputs are correct, these include values such as channel designation, sample dimensions, calculated wave speed, amplification, gain factor, and sampling frequency.
3. Run the script, it will prompt you to select a .csv file.
4. After running the script once, the user must analyze the strain vs. point number plot to determine the beginning and end of each wave. The beginnings of each wave must be input into the code as well as the wavelength. As the waves will not all be the exact same length, choose the value of the longest wave.
5. Run the script again, it should now produce stress-strain curves.
6. The script can be fine-tuned with graph axis limits and low pass filters.

APPENDIX K. MATLAB SCRIPT

```
clear all; close all; clc;
%% Select Trial
%The following command, when run, will prompt the user to select a .csv
%file of his or her choosing. This makes it user friendly and easier to
%select various trial runs rather than have MATLAB try and find the
%desirable file.

filename = uigetfile('../*.csv'); %This prompts you to select a file
filepath = strcat('C:\Users\zackj\Desktop\OScope data\',filename); %This will open the experimental data and pull the array we want without the things we dont

%% Initialize variables.
%The .csv produced by the Oscilloscope is formatted so that the data
%collected begins at row 21, column 1. This sets the boundaries of the
%data table we want imported

delimiter = ',';
startRow = 21;

%% Format for each line of text:
%   column1: double (%f)
%   column2: double (%f)
%   column3: double (%f)
%   column4: double (%f)
%   column5: double (%f)
% For more information, see the TEXTSCAN documentation.
formatSpec = '%f%f%f%f%f%*s%*s%*s%[^\n\r]';

%% Open the text file.
fileID = fopen(filepath,'r');

%% Read columns of data according to the format.
```

```
% This call is based on the structure of the file used to generate this
% code.
textscan(fileID, '%[^\n\r]', startRow-1, 'WhiteSpace', '', 'ReturnOnError', false, 'EndOfLine', '\r\n');
dataArray = textscan(fileID, formatSpec, 'Delimiter', delimiter, 'TextType', 'string', 'EmptyValue', NaN, 'ReturnOnError', false);

%% Close the text file.
fclose(fileID);

%% Create output variable
%This is the selected data from each of the resepctive channels.

MOAD = table(dataArray{1:end-1}, 'VariableNames', {'TIME','CH1','CH2','CH3','CH4'});

%% Clear temporary variables and rename data
%We clear all unnecessary variables here to enable the program to process
%the data at a faster rate. We also rename each of the channels with their
%proper names to make things easier when we calculate. We also transform
%the data table into an array to make the math functions simpler.

clearvars filepath delimiter startRow formatSpec fileID dataArray ans;

time    = double(table2array(MOAD(:,1))); %Time in seconds
SS_I    = double(table2array(MOAD(:,3))); %Stress Strain of Incident Bar
Vex_I   = double(table2array(MOAD(:,5))); %Excitation voltage of Incident
SS_T    = double(table2array(MOAD(:,2))); %Stress Strain of Transmitter Bar
Vex_T   = double(table2array(MOAD(:,4))); %Excitation voltage of Transmitter

clear MOAD

%% Input Constant Parameters
% Here we will  need to input our known parameters as well as perform a
% fourier calculation to reduce the noise of the system.
```

```
%50psi
L_S = 0.002916;    %m, specimen length
L_S_F = 0.001967; %m, specimen length, final
D_S = 0.006378;    %m, specimen diameter, original
D_S_F = 0.007823;   %m, specimen diameter, final
R_l = 0;            %Ohms, Resistance of lead wire, assume zero unless measured
R_g = 120;           %Ohms Nominal gage resistance
GF  = 2.14;          %Gage Factor of the strain gauge in use
Amp = 51;            %Op amp gain, depends on input resistor
Fs  = 5e6;         %S/s, Oscilloscope sample rate, changes with sample length of time
cutoff_freq = 20e4; %Hz, Low pass filter cutoff frequency 20e4
D_B = 0.018796;      %m, diameter of bars
K   = 160e9;         %Pa, bulk modulus of bars
rho = 8.08e3;        %kg/m^3, density of bars
E_B = 200e9;         %Pa, elastic modulus of bars
C_B = sqrt(K./rho)  %m/s, speed of sound in bars
C_B_1 = (2.*(28.125*0.0254))./(0.0003204 - 7.6e-06);
C_B_2 = (2.*(28.125*0.0254))./(0.000324 - 8.4e-06);
C_B = (C_B_1+C_B_2)./2 %m/s, speed of sound in bars, measured (=C_B if not measured)
wave_lwr_I  = 4918;  %sample point number, start of incident wave
wave_lwr_R  = 6473;  %sample point number, start of reflected wave
wave_lwr_T  = 6174;  %sample point number, start of transmitted wave
wave_length = 784;   %sample points, length of shortest of three waves
wave_upr_I  = wave_lwr_I + wave_length; %5700
wave_upr_R  = wave_lwr_R + wave_length; %6955
wave_upr_T  = wave_lwr_T + wave_length; %6934

%% Strain Calculation

%In order to calculate strain from the voltage outputs of the strain gages
%we must know the unstrained relationship between input and output
%voltages.
%This section takes an average over the first 1000 samples, a period when
```

```
%the bars should be in an unstrained state as triggering occurs at the
%midpoint of the dataset (5000).
V_out_unstrained_I = mean(SS_I(1:1001));
V_out_unstrained_T = mean(SS_T(1:1001));
V_in_unstrained_I = mean(Vex_I(1:1001));
V_in_unstrained_T = mean(Vex_T(1:1001)); % assumes trigger occurs at ~5000

%The following equations are sourced from Omega literature on using half
%bridge strain gage configurations. The literature assumes gages are
%located on the same branch and in opposite strains, however, this should
%be equivalent to equal strains on opposing corners of the bridge.
Vr_I = ( (SS_I./Vex_I) - (V_out_unstrained_I./V_in_unstrained_I) );
Vr_T = ( (SS_T./Vex_T) - (V_out_unstrained_T./V_in_unstrained_T) );

Strain_I = -((2.*Vr_I)./GF).*(1+R_l./R_g).*(1./Amp);
Strain_T = -((2.*Vr_T)./GF).*(1+R_l./R_g).*(1./Amp);
%% Plot Code
%Plot code to compare the straing of the incident bar and
%the strain of the transmitter bar vs. time.

figure('name','Incident and Transmitted Bars Strain Plot')
plot(time, Strain_I)
hold on
plot(time, Strain_T)
legend('Incident Bar Strain','Transmission Bar Strain','location','south')
xlabel('Time [s]')
ylabel('Strain, \epsilon')
xlim([-5.16e-5 0.0004204])
grid on

%% plot waves but against point number, not time
figure('name','Incident and Transmitted Bars Strain Plot, point based')
plot(Strain_I)
```

```
hold on
plot(Strain_T)
legend('Incident Bar Strain','Transmission Bar Strain','location','southwest')
xlabel('Time [s]')
ylabel('\epsilon')
%xlim([-5.16e-5 0.0004204])
grid on
%% Filtering

figure('name','FFT')

%FFT
%remember to adjust sample frequency

T = 1/Fs;
L = length(time); %length of time
t = (0:L-1)*T;
y = Strain_I; %signal to be examined
Y = fft(y);
P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);
f = Fs*(0:(L/2))/L;
plot(f,P1)
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')

%Design Filter
%remember to adjust sample frequency above
low = (cutoff_freq)/((Fs)*2);
[b,a] = butter(2,[low], 'low');
```

```
%Apply Filter
filt_Strain_I = filtfilt(b, a, Strain_I);
filt_Strain_T = filtfilt(b, a, Strain_T);

%remove filter
%filt_Strain_I = Strain_I;
%filt_Strain_T = Strain_T;

figure('name','Filtered Incident and Transmitted Bars Strain Plot')

plot(time, filt_Strain_I, 'linewidth', 1)
hold on
plot(time, filt_Strain_T, 'linewidth', 1)

legend('Incident Bar Strain','Transmitted Bar Strain','location','south')
xlabel('Time [s]')
ylabel('Strain, \epsilon')
xlim([-5.16e-5 0.0004204])
grid on

%% Calculate stress strain curves of materials, first using unsimplified equations

%We need to determine the starting and ending of each wave
Inc_Strain = filt_Strain_I(wave_lwr_I:wave_upr_I);
Ref_Strain = filt_Strain_I(wave_lwr_R:wave_upr_R);
Tra_Strain = filt_Strain_T(wave_lwr_T:wave_upr_T);

%Particle velocities at ends of each bar
v1 = C_B.*(Inc_Strain - Ref_Strain);
v2 = C_B.*(Tra_Strain);

%Average engineering strain and strain rate
Strain_rate_ave = (v1 - v2)./L_S;
```

```
t_int = 1/Fs;
Strain_ave = (C_B./L_S).*t_int.*cumtrapz(Inc_Strain - Ref_Strain - Tra_Strain);

%Convert bar and sample diameters into areas
A_B = (((D_B)./2).^2).*pi; %m^2
A_S = (((D_S)./2).^2).*pi;

%Sresses at both ends of specimen
Stress_1 = (A_B./A_S).*(E_B).*(Inc_Strain + Ref_Strain);
Stress_2 = (A_B./A_S).*(E_B).*(Tra_Strain);

%Plot stress at both ends of specimen, should be equal if in equilibrium
figure('name','Stress-Strain Curve, unsimplified')
plot(Strain_ave, Stress_1./1e6)
hold on
plot(Strain_ave, Stress_2./1e6)
ylabel('Stress [MPa], \sigma')
xlabel('Strain, \epsilon')
xlim([-0.005 .40])
legend('Interface 1','Interface 2','location','south')
grid on

%% Calculate stress and strain in the sample using simplifying assumptions to reduce equations
%simplify expressions
Strain_rate_ave = -2.*(C_B./L_S).*Ref_Strain;

t_int = 1/Fs; %s, amount of time between sample data points

Strain_ave = -2.*(C_B./L_S).*t_int.*cumtrapz(Ref_Strain);

Stress_ave = (A_B./A_S).*E_B.*Tra_Strain;

figure('name','Stress-Strain Curve, simplified')
```

```
plot(Strain_ave, Stress_ave./1e6, 'linewidth', 1)
ylabel('Stress [MPa], \sigma')
xlabel('Strain, \epsilon')
xlim([-0.005 .40])
ylim([0 2500])
grid on

% attempt 2 to change from engineering stress/strain to true stress/streain
true_stress = Stress_ave.*(1-Strain_ave);
true_strain = -log(1-Strain_ave);
figure('name','True stress vs. True strain')
plot(true_strain, true_stress./1e6, 'linewidth', 1)
ylabel('True Stress [MPa], \sigma')
xlabel('True Strain, \epsilon')
xlim([-0.005 .40])
ylim([0 2500])
grid on

figure('name','Strain Rate, simplified, vs time')
%create time vector
for i = 1:length(Strain_rate_ave)
   wave_time(i) = i.*t_int;
end

plot(wave_time, Strain_rate_ave)
mean(Strain_rate_ave)
xlabel('Time, [s]')
ylabel('Strain rate, [s^-1]');
grid on

eng_strain_stress(:,1) = Strain_ave;
eng_strain_stress(:,2) = Stress_ave;
true_strain_stress(:,1) = true_strain;
```

```
true_strain_stress(:,2) = true_stress;

%Save to .dat file, be sure to rename with each trial
dlmwrite('eng_strain_stress_4340_short_100psi_2.dat',eng_strain_stress)
dlmwrite('true_strain_stress_4340_short_100psi_2.dat',true_strain_stress)
```