DESIGN OF A SPLIT HOPKINSON PRESSURE BAR FOR DYNAMIC TESTING OF 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 design and fabricate a Split-Hopkinson Pressure Bar (SHPB) testing setup to study mechanical response of materials under dynamic loading. The SHPB apparatus is used to investigate the dynamic mechanical behavior of a wide range of common aerospace materials such as ceramics, polymers, composites and metals using one-dimensional stress wave propagation theory. The apparatus consists of three major components: the projectile launcher, incident bar, and transmission bar, with a representative material specimen placed in between the two bars. The projectile hits the incident bar causing a high amplitude stress pulse to form at the interface. This pulse propagates, as a one-dimensional wave, through the incident bar, the specimen, and into the transmission bar. The strain gauges mounted on both bars record the magnitude of the incident, reflected, and transmitted waves in bars. These signals can be analyzed to determine the specimen stress and strain. A Single Stage Gas Gun (SSGG) was designed to launch projectiles, ranging in length from six to eighteen inches, at velocities up to 100 m/s using pressurized air. The SHPB setup is mounted onto a rigid platform in order to provide structural support, vibrational damping, and adjustable alignment mounts to ensure one-dimensional wave propagation for different types of bars. The test setup described in this report features six-foot-long incident and three-foot-long transmission bars made up of Maraging 350 steel and 7075-T651 aluminum. The steel bars will be used to test metals and metallic alloys while the aluminum bars will be used for the testing polymers and composite samples.

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ACKNOWLEDGEMENTS

The authors would like to thank Dr. Nikhil Karanjgaokar for advising the project and providing technical support. They would like to thank Dr. Anthony Linn for help with the fabrication of the gas gun and the pressure bars. They would also like to thank the Washburn Machine Shops at Worcester Polytechnic Institute for help with fabrication and assembly of the apparatus. Finally, the authors sincerely appreciate the financial support for their work from Dr. Karanjgaokar's startup fund and the Department of Mechanical Engineering at Worcester Polytechnic Institute.

AUTHORSHIP

The team consisted of Bryan Adie (BA), Kieran Cochrane (KC), Anushrot Mohanty (AM), and Samuel Sierra (SS). BA and SS were responsible for the development of gas gun, which included the design, manufacturing and assembly of the gas gun, velocity detector, and the projectiles. AM and KC were responsible for design, manufacturing and assembly of the platform support, pressure bars, and the momentum trap. These responsibilities are also reflected in the writing of this paper. The respective sections were completed by persons responsible for the components.

For sections, such as the Abstract, Literature review, Conclusions and Recommendations, the writing process was collaborative. All four group members contributed to the section, and were involved in the editing process. As mentioned before, section of Chapter 3 and 4 were split and completed by the group members responsible for that specific portion.

1. INTRODUCTION

The Split Hopkinson Pressure Bar tests the mechanical behavior of materials at high strain rates utilizing one dimensional elastic wave propagation theory. This apparatus is commonly used in aerospace application to analyze the dynamic response of a given material by simulating impact conditions. Impact condition in aerospace applications can range from bird hitting a plane [1], to a landing gear strut experience sudden loads during landing, to composite structure behavior at high velocities [2].

Comprehensive material data are needed in industry prior to manufacturing a part. Selecting the appropriate material to construct the landing gear of an aircraft requires analysis of the material under sudden impact stresses such as those the part would undergo from routine flight operations. Testing a representative material sample involves placing a cylindrical specimen between two pressure bars, incident and transmission bars. The incident bar is impacted by a projectile inducing a stress wave which propagates along the incident bar. The stress wave then gets transmitted to the specimen and the transmission bar.

The strains in the pressure bars are measured by resistance-strain gauges and are recorded by an oscilloscope. One dimensional wave propagation theory and the analytical relations which describe how the stress wave propagates in the Hopkinson bar are described in this paper. Along with the stress wave being one dimensional, it is also elastic in the pressure bars. This produces dynamic stress-strain, and strain rate curves that describe the dynamic mechanical response of a given material.

The apparatus designed in the paper features a single stage gas gun to launch the projectile. There are two sets of projectile, incident and transmission bars. One set is made of Maraging 350 Steel to test metal specimens. The second set is made up 7075-T651 aluminum with a hollow transmission bar to test polymers and composite materials. The strain gauges on the bars are connected in a full Wheatstone bridge to an amplifier circuit and then connected to an oscilloscope. In addition, the apparatus allows for variable sizes of the two pressure bars as well as the projectile to test at various strain rates as well as correct for dispersions effect caused during experimentation.

2. LITERATURE REVIEW

2.1. Nomenclature

σ	=	amplitude of stress pulse	A	=	cross-sectional area
$\dot{\varepsilon}$	=	strain rate	E	=	Young's modulus
ε	=	amplitude of strain	m	=	mass
v	=	velocity	δ	=	energy difference
L_s	=	length of striker bar (projectile)	P	=	Pressure
C	=	elastic wave speed of material	$\forall$	=	volume of pressure chamber
ρ	=	density of material	C_p	=	pressure constant specific heat
t	=	time	C_v	=	volume constant specific heat

2.2. History

The Split Hopkinson Pressure Bar, also known as the Kolsky Bar, was first proposed in 1914 with the pioneering work of B. Hopkinson [3,7]. Hopkinson developed an apparatus to measure the pressure produced on a metal rod when impacted by a bullet. This came to be known as the Hopkinson Bar [4]. The pressure created from the ballistic impact would propagate through the main rod and would reflect off the free end. A smaller rod of the same material would trap the momentum of pressure wave and fly off into a device called the ballistic pendulum and be captured. Measuring the displacement of the pendulum would then determine the momentum of the small rod, and from that the amplitude of the pressure, or the stress in the main bar could be found. However, there were certain limitations to the model as described by R.M. Davies [5,8]. He mentioned that the magnetic adhesive force of the end piece limits the minimum pressure that could be measured with accuracy and that the apparatus did not allow for an accurate pressure-time history to be recorded. To overcome the disadvantages mentioned above, Davies introduced electrical measurement of the longitudinal displacement of the bar as well as the radial displacement of the cylindrical surface of the pressure bar. He presented the first dynamical axial and radial strain measurements in the Hopkinson bar using parallel plates and cylindrical condensers along with a double beam cathode ray oscillograph. The response from the cylindrical condensers described the pressure in the bar, while the response from the parallel plates described the displacement of the bar. As with the original Hopkinson bar, Davies described three limitations that were apparent in his experimentation model: 1) the pressure measurements that could be achieved by this model were limited by the elastic wave propagation assumption; 2) wave dispersion effects distort the propagating pulse and need to be accounted for; and 3) the pressure pulse is not uniform over the cross-section near the impact end.

One year later, H. Kolsky designed a modified Hopkinson bar setup that later was known as the Kolsky Bar or Split Hopkinson Pressure Bar [6]. Using similar design to that of Davies', Kolsky used parallel plate and cylindrical condensers but added a second, long, bar, the extension bar, and placed a material specimen between the pressure and extension bar. Figure 1 shows the apparatus used by Kolsky which became the inspiration for the modern Split Hopkinson pressure bar. In his paper (Ref. 6), Kolsky outlines a detailed procedure for calculating the stress-strain curve from the signals obtained by the condenser microphones, as shown in Fig. 1. Kolsky also recommended the use of lubricants to account for the interfacial friction between the specimen and bar ends. At changing strain rates, radial inertia of the specimen came into effect. Kolsky proposed length-to-diameter ratios of the specimen to eliminate inertia effects. Further improvements to the Kolsky bar did not occur till 1954, when Kraftt, Sullivan, and Tipper replaced the condenser microphones with strain gauges to measure the stress waves in the bar. They also introduced a gun to launch a projectile instead of an explosive detonator used by Kolsky. This provided repeatable results and created a trapezoidal shaped pulse which is now traditionally recognized as ideal for Kolsky bar experiments. In 1964, Lindholm presented the updated Split Hopkinson pressure bar with the aforementioned improvements; this device has become the template for all modern Kolsky bars in laboratories worldwide (Ref. 3).

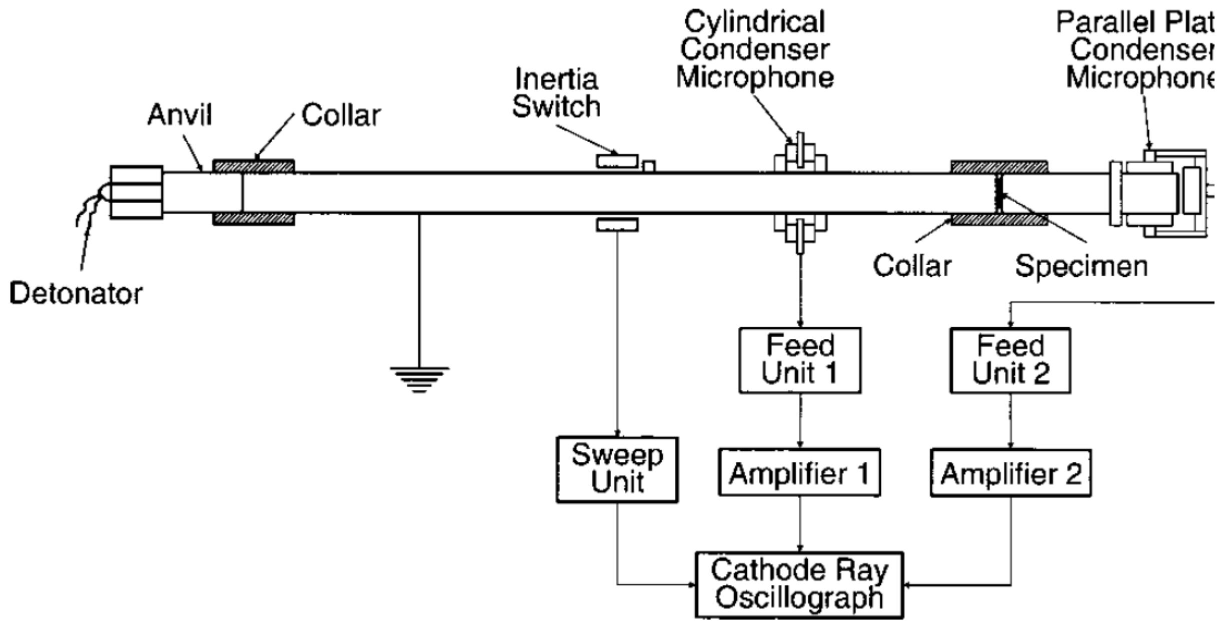


Figure 1. Schematic of Kolsky's apparatus. Reproduced from Fig. 8, Ref. 7.

A conventional Split Hopkinson bar consists of three major components: a loading device, bar components, and a data acquisition & recording system, as shown in Fig. 2. The loading device most commonly used in experiment is a gas gun. "Gas guns have been found to be efficient, controllable, and safe for Kolsky compression bars (Ref. 3)." The projectile is launched by a sudden release of the compressed air in the pressure chamber and accelerates in a long gun barrel until it impacts the end of the incident bar. The velocity of the projectile can be controlled by changing the pressure within the chamber resulting in repeatable impacts.

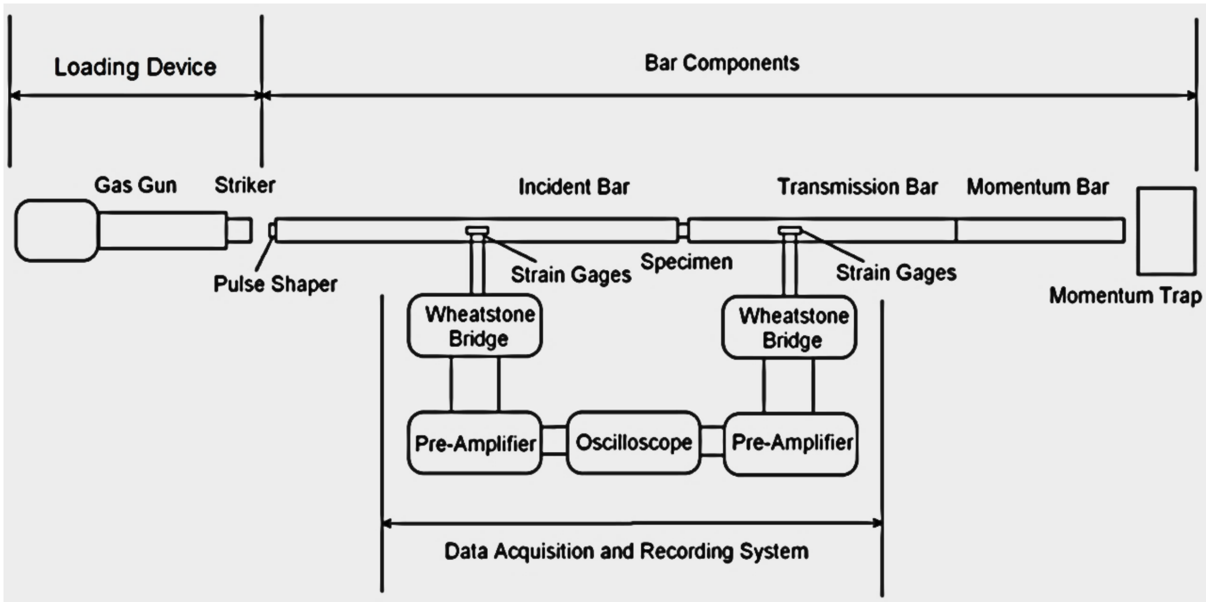


Figure 2. Conventional Split Hopkinson Pressure Bar. Reproduced from Fig. 1.6, Ref. 3.

As mentioned before, the Split Hopkinson bar consists of a projectile, or striker bar, an incident bar, and a transmission bar. The three bars are of the same material and diameter. These bars are usually high strength material because the stress waves in the bar are measured by surface strain during experimentation. Thus, the bar material is required to be linearly elastic with a high yield strength. The bar material is also homogenous and isotropic. It is imperative that the bars are perfectly aligned along a common straight axis, which is also the loading axis of the system. While being physically straight, the whole bar system must be allowed to move freely in their supports with minimal friction. The incident bar is designed to be atleast twice as long as striker bar to avoid overlapping of the incident and reflected pulses. The material specimen is sandwiched between the incident and transmitted bar and aligned with the common loading axis of the system as well. An optional momentum bar and momentum trap device is sometimes included at the end of the system as shown in Fig. 2. Since 1954, strain gauges have become the standard measurement technique for Split Hopkinson bar experiments. Strain gauges are attached symmetrically on the bar surface. A Wheatstone bridge is used to condition the signals acquired from the strain gauges. Since the output voltage from the Wheatstone bridges are usually on the scale of milli-volts, signal amplifiers are necessary to record the low-amplitude signal with an oscilloscope.

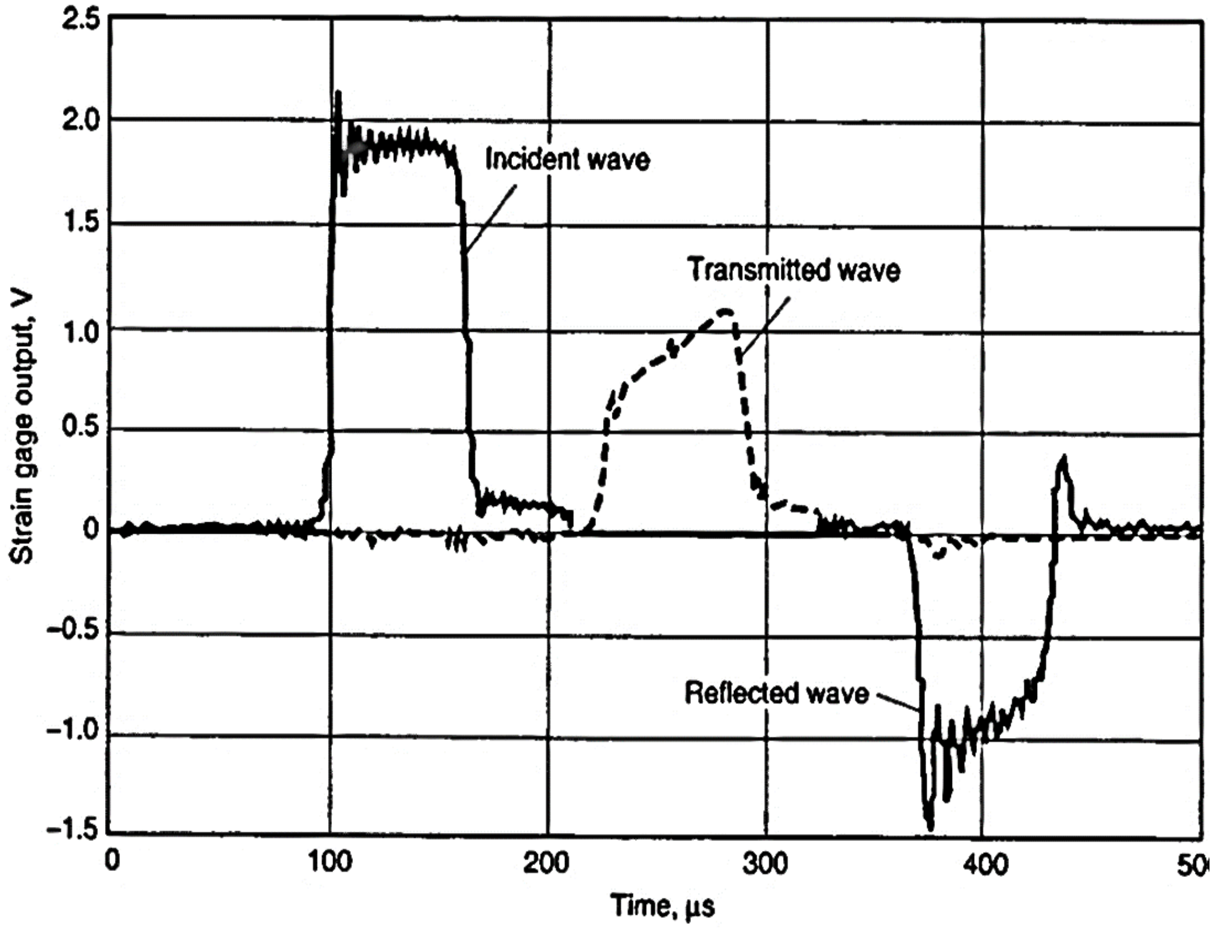


Figure 3. Strain gauge signals from a Split Hopkinson Bar. Reproduced from Fig 17, Ref. 7.

In a traditional Split-Hopkinson bar experiment, the stress wave produced from the impact of the projectile on the incident has a trapezoidal shape. When the wave propagates through the incident bar and reaches the specimen interface, part of it is reflected back into the incident while the rest transmits into the specimen and the transmission bar. When the wave initially passes through the specimen, it gets reflected back and forth within the specimen and compresses it. The interaction of the stress wave and the specimen-transmission bar interface is what produces the transmission signal. To ignore this ringing in the specimen, equilibrium stress condition in the specimen is assumed. Thus, three primary signals from the strain gauges are recorded: the incident wave, the reflected wave, and the transmitted wave. Figure 3 shows the strain gauge signals as acquired from a typical Split Hopkinson bar test. The incident and reflected wave are both recorded by the strain gauges mounted on the incident bar, while the transmitted signal is recorded by the strain gauges on the transmitted bar. The following are assumptions that need to be satisfied to validate a Split Hopkinson bar test: 1) the stress wave propagation in the bars is one dimensional; 2) the specimen-bar interfaces remain plane at all times; 3) the specimen is in stress equilibrium after the initial ringing period; 4) the specimen is not compressible; 5) friction and inertia effects in the specimen are minimum.

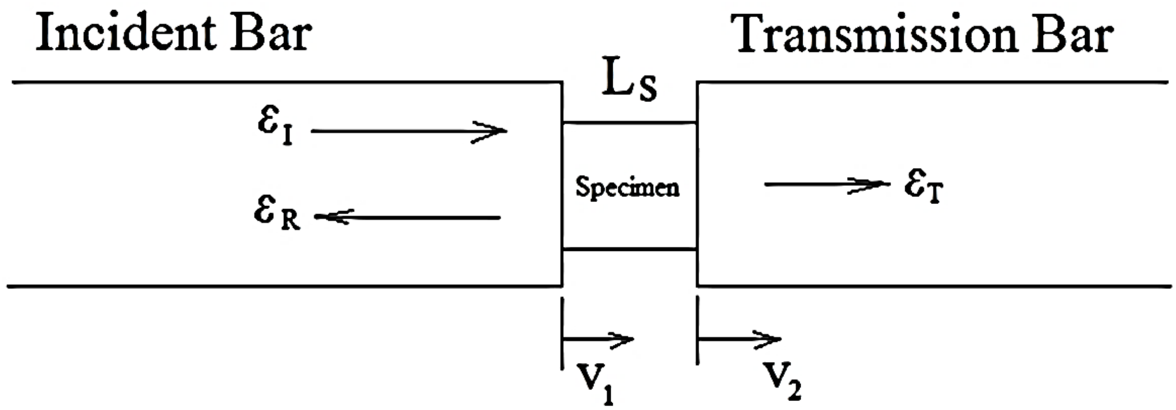


Figure 4. Test section of a Split Hopkinson Pressure Bar. Reproduced from Fig 1.10, Ref. 3.

Figure 4 shows a diagram of the test section. With the assumption of one dimensional wave propagation, the particle velocities at both end of the specimen can be found from the measured strain pulses,

$$v_1 = C_B(\varepsilon_I - \varepsilon_R) \tag{1}$$

$$v_2 = C_B \varepsilon_T \tag{2}$$

where the subscripts I, R, and T refer to the incident, reflected, and transmitted pulses respectively. The average engineering strain rate and strain in the specimen are,

$$\dot{\varepsilon} = (v_1 - v_2)/L_s = C_B(\varepsilon_I - \varepsilon_R - \varepsilon_T)L_s^{-1} \tag{3}$$

$$\varepsilon = \int_0^t \dot{\varepsilon} dt = L_s^{-1} C_B \int_0^t (\varepsilon_I - \varepsilon_R - \varepsilon_T) dt \tag{4}$$

As mentioned before, the specimen is assumed to be in a stress equilibrium condition during experimentation. Additionally, the specimen also deforms uniformly so that the response averaged over its volume is a nearly accurate representative of material behavior. It is important to note that the derived equations above and below use only the known properties of the bars and measured strain quantities from experimentation. These equations also use non-dispersive wave propagation assumptions. Given the calculated strain in the specimen the stresses at the two ends of the specimen can be found with elastic relations,

$$\sigma_1 = A_B A_s^{-1} E_B (\varepsilon_1 + \varepsilon_2) \tag{5}$$

$$\sigma_2 = A_B A_s^{-1} E_B \varepsilon_T \tag{6}$$

where B and S refer to the bar and specimen. With stress equilibrium in the specimen assumed,

$$\sigma_1 = \sigma_2 \tag{7}$$

$$\varepsilon_I + \varepsilon_R = \varepsilon_T \tag{8}$$

thus Eq. (3), (4), and (6) can be simplified to,

$$\dot{\varepsilon} = -2 C_B L_s^{-1} \varepsilon_R \tag{9}$$

$$\varepsilon = -2 C_B L_s^{-1} \int_0^t \varepsilon_R dt \tag{10}$$

$$\sigma = A_B A_s^{-1} E_B \varepsilon_T \tag{11}$$

These equations are used to describe the stress-strain histories of the specimen during a conventional testing of a Split Hopkinson pressure bar.

2.3. Other Types of Dynamic Testing

Charpy notch impact test, or Charpy test, operates by setting a pendulum to a specific height, letting it swing into a prepared specimen that has a scientifically agreed upon standard notch in it. The basis of the Charpy Impact test is energy conservation, when the pendulum hits the notched specimen, some of the potential energy is lost due to transfer of kinetic energy to the specimen. The transfer of energy is shown by the pendulum's oscillations having a smaller amplitude than the unencumbered, or no specimen case. The difference between the initial and final height of the striker, multiplied by its weight, yields the work absorbed by the rupture. One of the benefits of this method is that is one of the more cost-effective material testing procedures with respect to acceptance of materials and recording data. However, the problem with this testing methods is the data that is recorded from this can only compare its results with itself.

Another type of impact or high strain rate testing is the use of a drop tower. A traditional drop tower is an apparatus that operates by releasing a guided mass from a variable height to fall onto a specimen of unknown properties. There are a few problems with this type of testing, with the representative specimen being vertical, effects of gravity now need to be taken into account. Therefore, now the mass of the specimen needs to be known. In addition to this, it is hard to optimize the shape of the pulse for a drop tower. To get the ideal shape for testing polymer, ceramic and metal specimens, many different masses would be needed to get reliable results. With the SHPB, no material properties of the specimen need to be known. In addition, it is easier to create an optimum pulse shape for different specimens by varying the speed of the projectile with the Single Stage Gas Gun or changing the length of the projectile. Both methods of drop tower testing and the Charpy impact testing share a similar issue that also needs to be taken into account, a so called double hit caused by rebound of the impactor can occur in case when the specimen is not fully broken by the first blow of the impactor. This creates additional strain waves and additional deformation to the specimen changing propagation of the strain waves.

3. DESIGN AND MANUFACTURING

The SHPB apparatus being constructed consists of five major parts:

1. Platform support system,
2. Single Stage Gas Gun,
3. Velocity detector and data acquisition system,
4. Pressure bars, and
5. Momentum trap.

Throughout this design process, SolidWorks® was used to create 3D models to streamline the design process by easily implementing changes and enabling creation of easy-to-read, industry-standard drawings. Additionally, most of the construction was made from steel, and to reduce weight aluminum was used wherever the structural loads were lower in the design of this apparatus.

3.1. Platform Support System

The design of the apparatus went through several design revisions based on previous work done in other papers, cost effectiveness, and structural consideration. The apparatus at Caltech and at other research labs used a similar design with the use of steel I-Beams as the bench table and sawhorse legs for support. All these systems were low to the ground to increase stability and reduce vibrations. Hence the total height of the apparatus was set to 36 in (3 ft). Figure 5 shows the entire assembled apparatus as it currently stands.

Figure 5. Fully assembled Split-Hopkinson Apparatus

Initially, two designs were proposed. The first being the conventional I-Beam structure design consisting of a steel I-Beam bed and sawhorse legs for support. The high cost for the aforementioned design as per initial cost analysis dictated the need for exploration of other cheaper designs providing the same amount of structural support. The idea of using a thick metal plate instead of the I-Beam as the bed was proposed but was found to be too expensive.

One of the major considerations in this design of the apparatus was the alignment of the entire system. Having the SSGG and SHPB apparatus on different surfaces was more likely to cause the entire system to be prone to misalignment of bars and thus violating the 1D assumptions associated with the SHPB analysis. It was imperative that the entire apparatus be extremely straight horizontally, with no noticeable deviations. This is crucial for running accurate tests and getting viable data as well as maintaining a safe test environment.

As the design process continued, further requirements were added for the final design. The ability to easily modify the setup and replace the individual components was deemed to be one of the first requirements. This significantly reduced the number of unique machined parts and instead we chose to use parts that are readily available from vendors, thus being easy to replace if one fails. In accordance with this policy, only two parts in the final setup had to be designed and subsequently machined. One of these parts were the Delrin bushings, which were bored and cut into 0.75in (19.05mm) pieces to be used for providing vertical support to the incident and transmission bars and allowing these bars slide with minimal friction. These bushings would be placed in the shaft support (purchased from McMaster-Carr). The second machined part is the mounting block which is used to provide a more stable resting position for the shaft support, as well as align the bars with the barrel of the gas gun. This will be shown later in the section.

At the beginning of the project, it was decided that the gas gun would be placed on a separate table or fixture to ensure that the recoil caused from the release of the gas would not cause any extra vibrations on the system. Initially, aluminum structural I-Beams were considered for the support platform, but their low inertia raised concerns with respect to their long-term ability to withstand recoil forces caused by the gas gun. Further cost analysis showed that using steel I-Beams would be more economical as well as structurally sound enough for the gas gun to be mounted on the beam as well.

The steel I-Beams were capable of handling the structural load of the SHPB, but due to the rusted surfaces the bars would not be aligned if the apparatus was placed immediately on top of the beams. The beams were de-rusted, sanded, and painted to ensure that the surface was flat and would be protected from further rust. This process greatly reduced the difficulty associated with the alignment of the bars.

Many other design features were changed and removed. For example, one proposal was to use rails so that the mounting blocks could be moved along the I-Beam and be adjusted for different bar lengths. However, this idea complicated the design of the mounting block due to the keyhole shape that would have needed to be machined in order to fit on the rails as well as increasing the amount of work that would need to be done on the I-Beam to mount the rails onto it. Hence this idea was scrapped and it was decided that the mounting blocks can be attached directly to the I-Beam itself.

As mentioned before, most of the SHPB systems used sawhorse legs for support. These legs would be something that would have to be manufactured. To further simplify the design, a simple "T" shaped design was used for the legs. Hollow steel square tubing would be welded together to form the feet. This reduced the amount of materials that would need to be purchased, and made the cuts simpler. The steel tubing was 2" x 2" (50.8 mm x 50.8 mm) with a wall thickness of 5/16" (7.94 mm). Each I-Beam would have three legs, with the first I-Beam having a 4th leg to support the added weight of the gas gun. At the base of this "T" located 1" (25.4 mm) from each end was a ½" (12.7 mm) hole to allow for leveling feet purchased from McMaster-Carr. These feet allowed for additional vertical alignment for the system which was necessary due to the unevenness of the lab's floor. Figure 6 shows the support leg design.

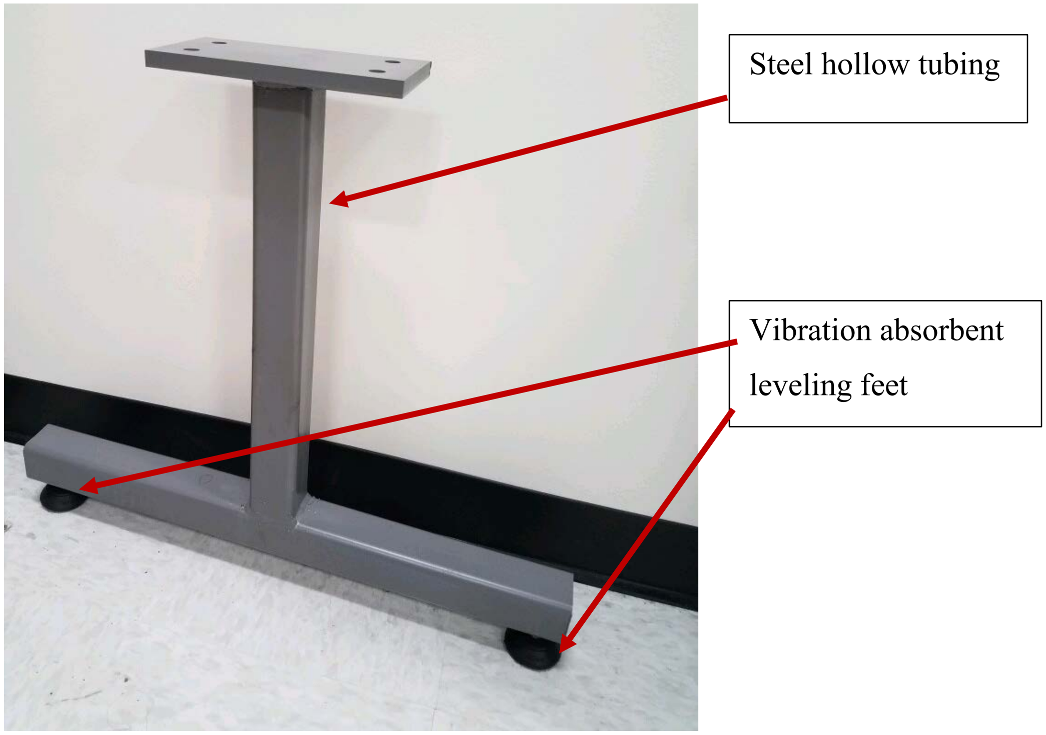


Figure 6. Image of the welded support legs for the steel I-Beams

Once the design was approved, machining could begin. The first part to be machined was the Delrin bushings through the use of CAM tools. The process was coded in Esprit, and then transferred to a lathe. Six bushings with the OD of 1.510" (38.35 mm) and an ID of 0.779" (19.79 mm) were machined.

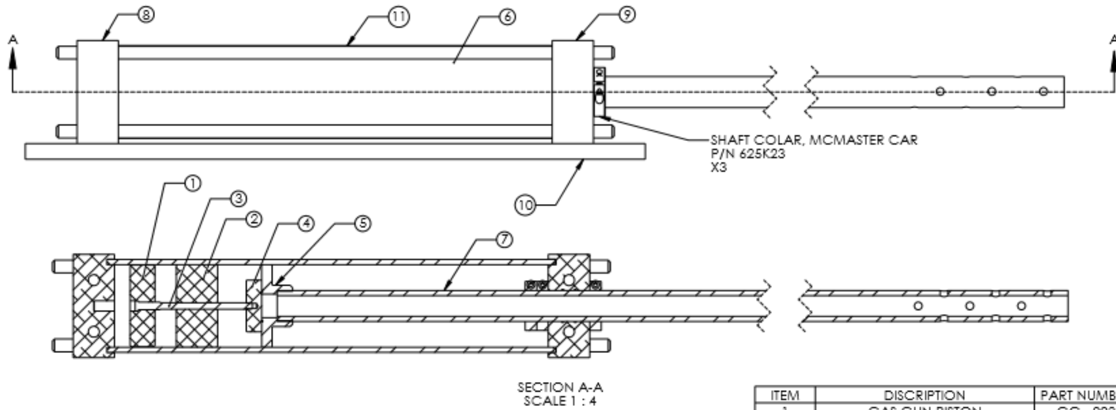
In order to keep the bars aligned and steady, the bars required a support structure. After researching various SHPBs, it was determined that an off the shelf collar would be cheaper and easier to acquire compared to the typical method of machining a hole in a square steel sheet mounted onto an I-Beam. The linear shaft collar acquired from McMaster-Carr was cheaper in comparison to materials and labor as well as can accommodate a wider variety of bars. Bushings must be used in both of these methods, but the shaft collar is adjustable allowing for a tight and even fit around the bushing ensuring that when the bars are in motion, the bushings do not move with them.

With the SSGG mounted on the I-Beam, the shaft collars needed to be raised in order for the bars to be at the same height as the barrel. As mentioned previously the initial method for the mounting of the shaft collar itself was to use a rail system, but it was determined that individual blocks machined to add the needed height for the vertical alignment would be the better alternative. These blocks were cut from an initial square stock of steel 1.75”x1.75”x72” into 9 blocks with the dimensions 1.75”x1.75”x8”**.** Each block now need to be milled by ¼” on the top surface as well as a set of 4 holes, 2 clearance holes of ½” to connect the blocks to the I-Beam as well as 2 tapped holes of 5/16” for the shaft collar to be attached. This process was coded in ESPRIT® and the blocks were placed individually into a CNC machine to be altered.

3.2. Single Stage Gas Gun

The main requirements for the design of the Single Stage Gas Gun (SSGG) was to be able to operate at a max pressure of 150 psi. Be able to fire projectiles at various pressures up until the max pressure. Be able to fire both margining steel and 7075 aluminum projectiles that ranging in length up to 18 inches and diameters just less than an inch.

To fulfill these requirements, a base model was used as reference. The original model for the Single Stage Gas Gun (SSGG) was based off a SHPB from California Institute of Technology (Caltech) which is still used today. Upon evaluation, some parts of the design were determined to be outdated and unnecessarily complex. The changes led to benefits such as cheaper costs,



ITEM	DISCRIPTION	PART NUMBER	QTY.
1	GAS GUN PISTON	GG - 003	1
2	GAS GUN GUIDE, VALVE	GG - 004	1
3	GAS GUN PIN, VALVE	GG - 005	1
4	GAS GUN PLATE, VALVE	GG - 006	1
5	GAS GUN SUPPORT	GG - 007	1
6	GAS GUN TUBE	GG - 008	1
7	GAS GUN BARREL	GG - 009	1
8	GAS GUN CAP, RELEASE END	GG - 010	1
9	GAS GUN CAP, BARREL END	GG - 011	1
10	GAS GUN PLATE, MOUNTING	GG - 012	1
11	GAS GUN TIE-RODS, MOUNTING	GG - 013	1

Figure 7. Drawing of the single stage gas gun with components labeled

increased machinability and a lower overall weight. A drawing of the assembly, excluding valves, is shown in Fig. 7, please refer to this figure when a part number is stated.

One of the most substantial changes involved resizing the pressure canister component of the gun which lead to the majority of the design changes. Specifically, the canister, which needed to be machined was replaced with an off-the-shelf tube, reducing the wall thickness from 1.45 inches (36.83 mm) to 0.25 inches (6.35 mm). The predominate reason for the high wall thickness was to have the inlet valve port be on the canister, however this inlet created an unnecessary stress concentration point was causing failure at 700 psi. Removing this port allows for that reduction and creating a uniform canister that can withstand pressures greater than 700 psi, to achieve a predetermined safety factor of five. This change was also necessary because a scarce amount of machining companies were able to manufacture this part, and at a much higher cost. Therefore, the input valve port was incorporated into the Barrel End Cap of the assembly (GG-011). The Gas Gun Caps (GG-010/GG-011) were created to replace circular endcaps that screwed into the canister and needed separate mounts to attach to the I-beam, enabling the SSGG assembly to be easily mounted and creating the necessary seal (Fig. 7-8).

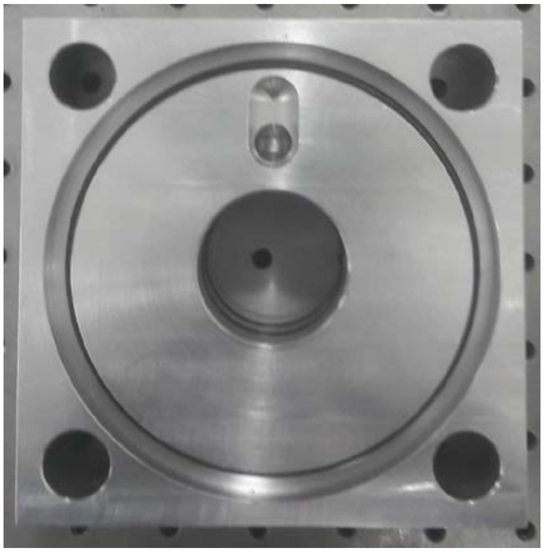


Figure 8. Gas gun barrel end cap

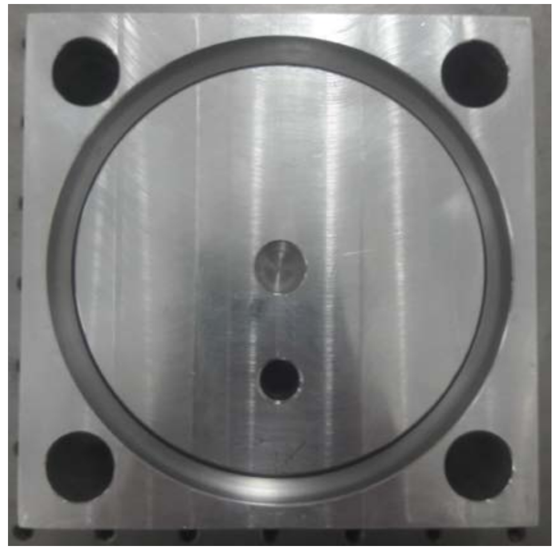


Figure 9. Gas gun release end cap

This seal was created by removing the threading on the canister and creating a groove with an O-ring that the edges of the canister fit into. To keep the GG-010 and GG-011 together, four tie rods (GG-13) were used according to dimensions of Douce Hydro Series DHI - MX2 heavy duty hydraulic cylinders' specifications. One part that was completely removed from the original design was a clamping system that needed to be machined and was replaced with shaft collars bought off-the-shelf. A base plate (GG-012) was added so the SSGG to enable use in other applications if necessary. The fabrication of all the components of the SSGG was done by WPI Professor Anthony Linn. Additionally, the assembly guide and the operations manual for the SSGG can be found in Appendix A.

Prolonging the life of the SSGG was heavily considered during the design process. For instance, hex nuts were used in the internal piston component of the gas gun (Fig. 9) to protect the threading of the pin (GG-005) from any damage. This way the nut would distribute any impacting force over multiple threads instead of just the first series. Additionally, anytime there was a direct connection from steel to aluminum, some interim component was placed to ensure the hard steel would not strip the soft aluminum of its threads. That is why the base plate has steel inserts, the lower thread count on the outside of the insert will wear away at the aluminum less than the high thread count of the steel bolts. Additionally, there are special steel washers in-between the nuts on the tie rods and the end caps. This way the nuts would not dig into the aluminum caps when tightening the rods. The other protective considerations that were implemented, was to first reduce the potential damage of assembling the SSGG by apply a thin layer of lubricant on the I.D. of the canister. The second additional consideration was applying a protective coating of paint over the O.D.s of the canister and tie rods to prevent the steel components from rusting.

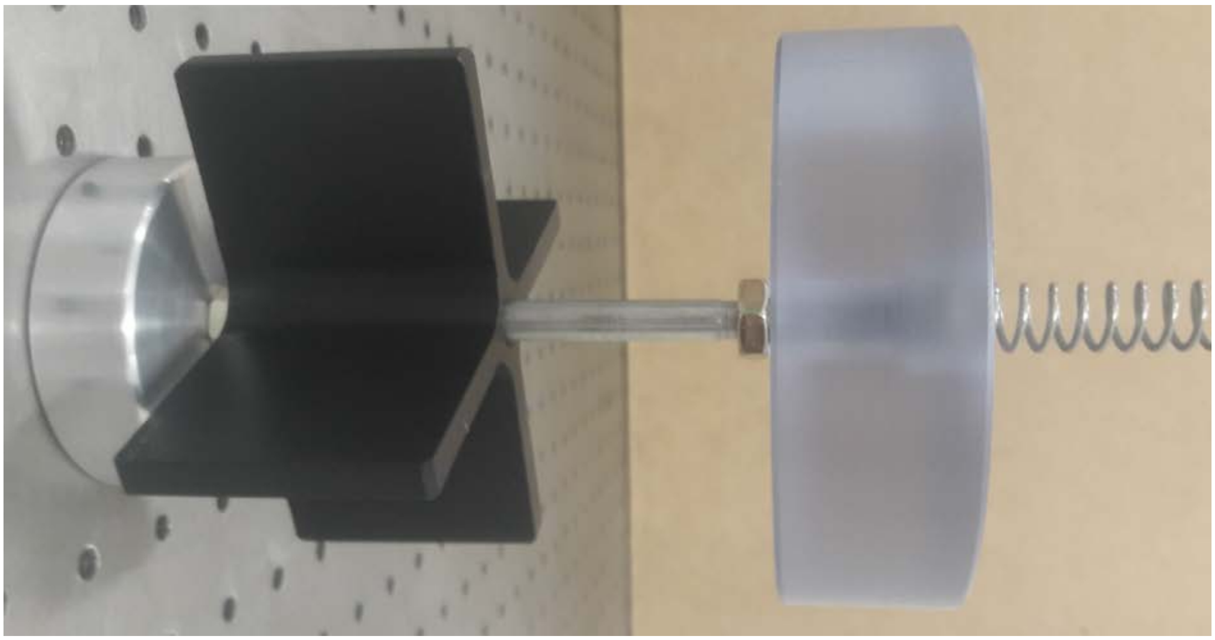


Figure 10. Internal piston components of the gas gun

The next consideration for the SSGG was the valves. However, the actual method of how this gas gun operates will need to be explained first.

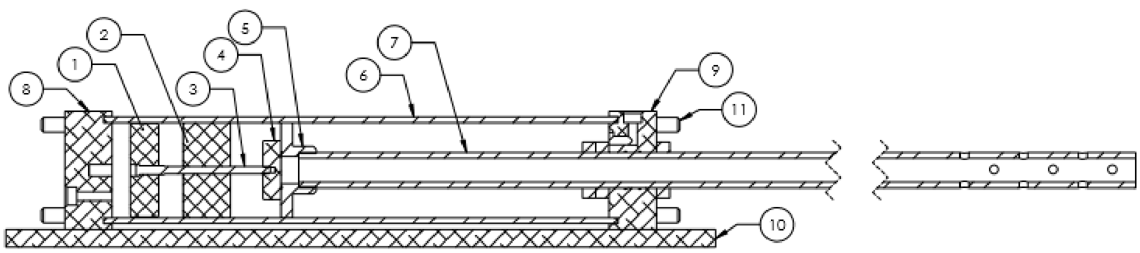


Figure 10. Section view of the SSGG

For the SSGG to fire, a pressure differential needs to be created. With reference to Fig. 10, this is accomplished by component 1 (GG-002) having a minimal radial difference between itself and the I.D. of the canister. Then when the pressure is released from the outlet port on component 9 (GG-

010) only the volume of air in-between components 1 and 8 is instantaneously released, creating a volume of low pressure. The air in the rest of the canister is still at a high pressure so the movement of gas from high to low pressure pushes the entire piston (components 1-4) towards the release end. This also essentially blocks outlet port of component 8. When component 4 (GG-006) moves, the seal that it and component 5 (GG-007) has breaks and because the air inside the barrel is at atmospheric pressure, a new low pressure system is created. All the remaining air in the canister is then pushed through the barrel and propels the projectile. After the gas is released from the canister, the spring moves the piston back re-creating the seal between components 4 and 5. The barrel has relief ports towards the end so the pressure can escape the barrel in a way that will not interfere with the system.

Now that the firing operation is known, the valve system can now be discussed. To minimize the chance for any leaks between the end caps and the valve systems, SAE threaded adaptor components were used, these feature an o ring to create the necessary seal. For safety precautions, a bleed valve needed to be incorporated so it was possible to depressurize the canister without firing. A pressure gauge was added to both ports to ensure both volumes were at the same pressure and component 1 was not closing off the volume between component 1 and 8. A silencer was added to the exhaust port because when the canister was pressurized past 50 psi, ear plugs were needed. To prevent ear damage at higher pressures the high flow rated silencer reduces the noise and minimizes the amount of back pressure produced.

To propel projectiles with diameters smaller than an inch, sabots were designed. These sabots were rings that were press fit onto each of the six projectiles. For the two 18 inch projectiles, it was determined best to put four sabots on each, the 12 inch projectiles were given three each and the six-inch projectiles were given two each. Figure 11 shows the entire assembled gas gun as constructed in this project (with collar that will be explained in the next section and barrel supports).

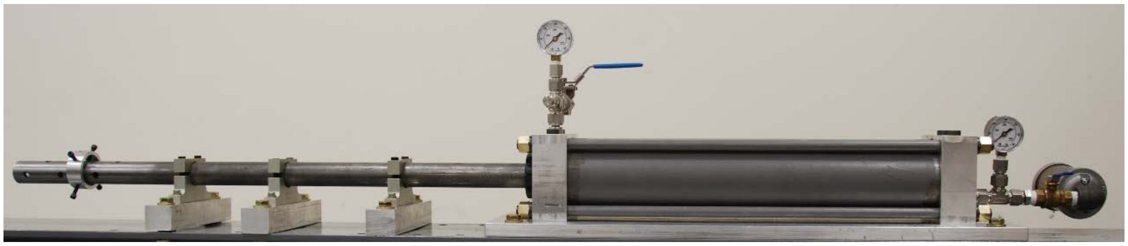


Figure 11. Image of the fully assembled gas gun

3.3. Velocity Detector and Data Acquisition System

There are three parts that needed to adapt to the new setup and those were the projectile, a sabot, and a laser trigger system. The projectile needs to vary in length and material. It needs to vary in material accordingly to the specimen because the difference in material would create impedances in the stress wave and result in unreliable data. The variance in length affects the amplitude of the stress wave which is needed for softer materials. The sabot is needed for alignment and efficiency purposes. With regards to alignment, these tests only produce usable data if they are one-dimensional so the sabot makes sure the center of the projectile hits the center of the incident bar. It also acts like a plug to make the pressurized gas not leak out of the sides of the projectile so maximum speed can be acquired.

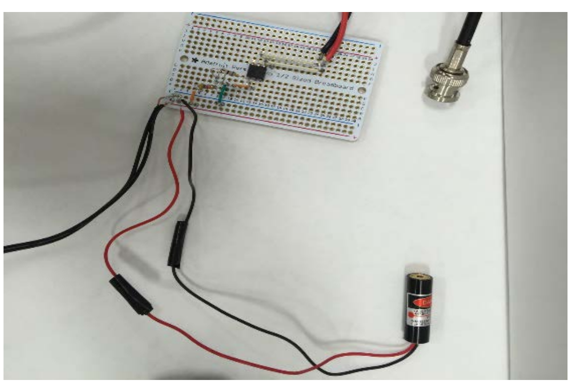


Figure 12. Picture of Photodiode and Laser

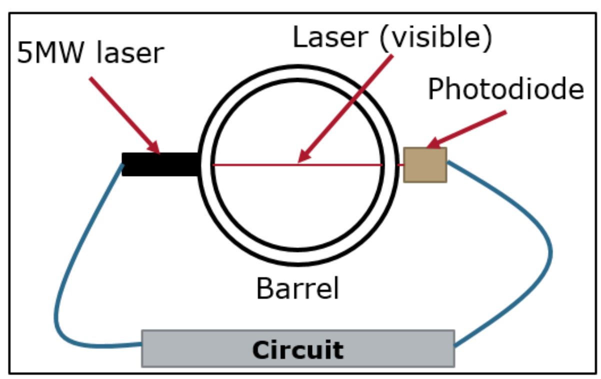


Figure 13. Figure of Laser Trigger System

Figures 12 and 13 show the light interruption circuit consists of a laser and photodiode used for calculation of projectile velocity. Generally, such circuits are used for triggering a camera flash in order to capture high speed objects so it had to be adjusted to the needs of this project. A simpler version of the circuit was implemented in this project which consisted of the photodiode connected to the oscilloscope with a powered laser pointed at it. The laser and photodiode were mounted on a collar which can be mounted on the gun barrel. The collar is aligned so that the light from the laser passes through the holes in the gun barrel and falls on the photodiode. When the projectile passes through the barrel, the front of the projectile interrupts the light path and the voltage of photodiode changes abruptly. As the rear of the projectile passes, the path of laser light is restored and the voltage of the photo-diode recovers to its original value. Figure 14 shows a schematic representation of voltage Vs time graph obtained using the oscilloscope. As stated earlier, the time for which the circuit is interrupted corresponds to the length of the projectile.

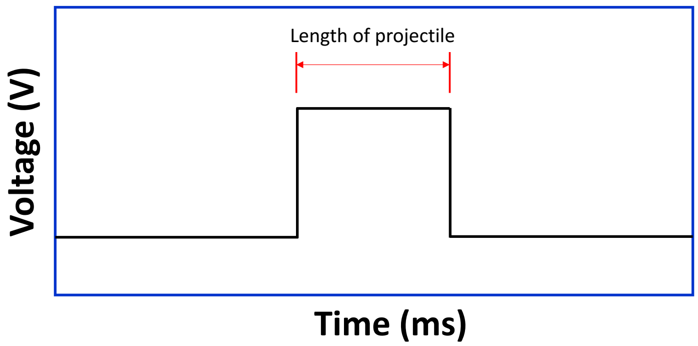


Figure 14. Schematic representation of the Voltage vs Time Graph for Calculating Velocity of the Projectile

3.4. Pressure Bars

In order to facilitate the testing of hard metal samples as well as soft polymers and composites, 3 sets of pressure bars were acquired. The first set of incident, transmissions, and projectile bars were of VascoMax Maraging 350 steel, acquired from Service Steel Aerospace. The second set of bars was made of 7071-T651 Aluminum, acquired from MSC Direct. The transmission bar of the aluminum set was then hollowed and fitted with end caps to facilitate the testing to softer materials. This is discussed further in the paper. The hollow transmission bar had a wall thickness of 1/16 inch (1.59 mm) Table 1 lists the physical properties of the pressure bars [9].

Table 1. Physical properties of pressure bar materials

Bar Material	Density, g/cc	Poisson's ratio	Tensile strength, MPa	Yield strength, MPa	Young's Modulus, GPa
VascoMax Maraging 350 Steel	8.08	0.31	2413	2344	210
7075-T651 Aluminum	2.81	0.33	572	503	71.7

The acquired pressure bars had a common diameter is 0.75 in. This diameter was partly determined from the suggested length to diameter ratio (20:1) of the pressure bars, as well as the allowable projectile diameter that could be fired by the gas gun. The length of the incident bar was set at 72 inches (1.83 m), while the transmission bar's length was 36 inches (0.914 m). There are 3 projectiles of lengths varying from 6 inches (.152 mm) to 18 inches (0.457 m). The bars are supported with Delrin® bushings on Easy-Access Base Mounted Shaft Supports bought from McMaster-Carr. Figure 15 shows the supports for the pressure bars. The shaft supports are mounted on aluminum blocks which raise the shaft supports by 1.5 inches (0.0127 m) to maintain alignment with the barrel of the gas gun. The aluminum blocks are bolted on the I-Beam. The incident and transmission bars move freely in the longitudinal direction through the Delrin ® bushing. A momentum trap at the left end of the transmission bar acts as a stopper.

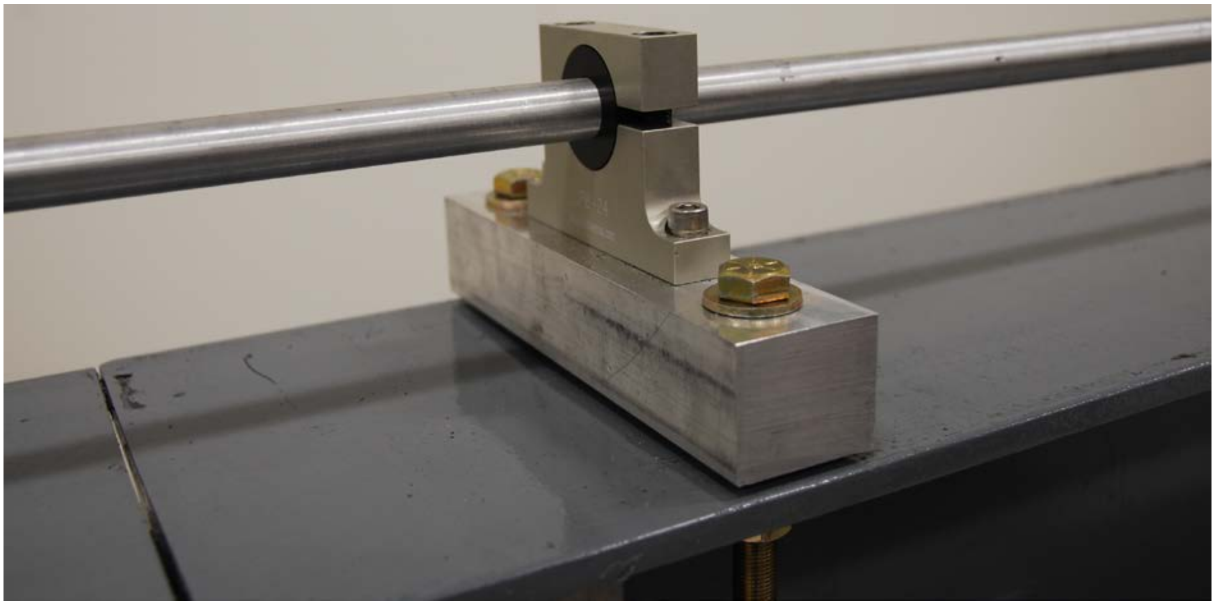


Figure 15. Support for the pressure bars

An alternative set up to the SHPB apparatus is to use a hollow transmission bar in combination with a solid incident bar. This combination allows for the testing of softer materials such as polymers as the bar sensitivity has been increased. This increase in bar sensitivity occurs from the reduction of the cross-sectional area of the transmission bar. When this is done, the transmission bar works as a linear elastic stress/strain amplifier [3]. Since the incident and transmission bars in this case have different cross-sectional areas, the equations to calculate the strain rate and strain must be modified into;

$$\dot{\varepsilon}(t) = c_0 l_0^{-1}(1 - A_i A_t^{-1})\varepsilon_i(t) - c_0 l_0^{-1}(1 - A_i A_t^{-1})\varepsilon_R(t) \tag{12}$$

$$\varepsilon(t) = c_0 l_0^{-1}(1 - A_i A_t^{-1})\int_0^t \varepsilon_i(\tau)d\tau - c_0 l_0^{-1}(1 - A_i A_t^{-1})\int_0^t \varepsilon_R(\tau)d\tau \tag{13}$$

With A_i and A_t representing the cross-sectional areas of the solid incident bar and hollow transmission bar respectively.

3.5. Momentum Trap

To arrest the momentum of the transmission bar during testing, a simple momentum trap was constructed which was clamped onto the I-Beam 6 inches (152.4 mm) behind the end of the transmission bar. This momentum trap consists of five layers of different materials which had increasing dampening properties to ensure that the transmission bar was not only stopped, but the momentum absorbed. If the momentum of the transmission bar was not completely absorbed, the bar could ricochet into the specimen causing more deformation as well as skewing the data collected by the strain gages. The first layer consists of clay in order to form an adhesive contact with the end of the transmission bar to prevent the bar from ricocheting. The clay also served to catch the bar and guide it into the other layers in a straight line to ensure that the bar itself did not undergo any deformity. The second layer consists of a 6” X 6” X 1/2” (152.4 mm X 152.4 X 12.7 mm) shock absorbent polyurethane. The second and third layers consist of 8” X 8” X 1/2” (203.2 mm X 203.2 mm X 12.7 mm). The final layer consists of a 12” X 12” X 1” (304.8 mm X 304.8mm X 25.4 mm) 1018 mild steel plate. These plates are attached together through the use of two threaded rods and two L-brackets which are clamped to the beam. Figure 13 shows the momentum trap.

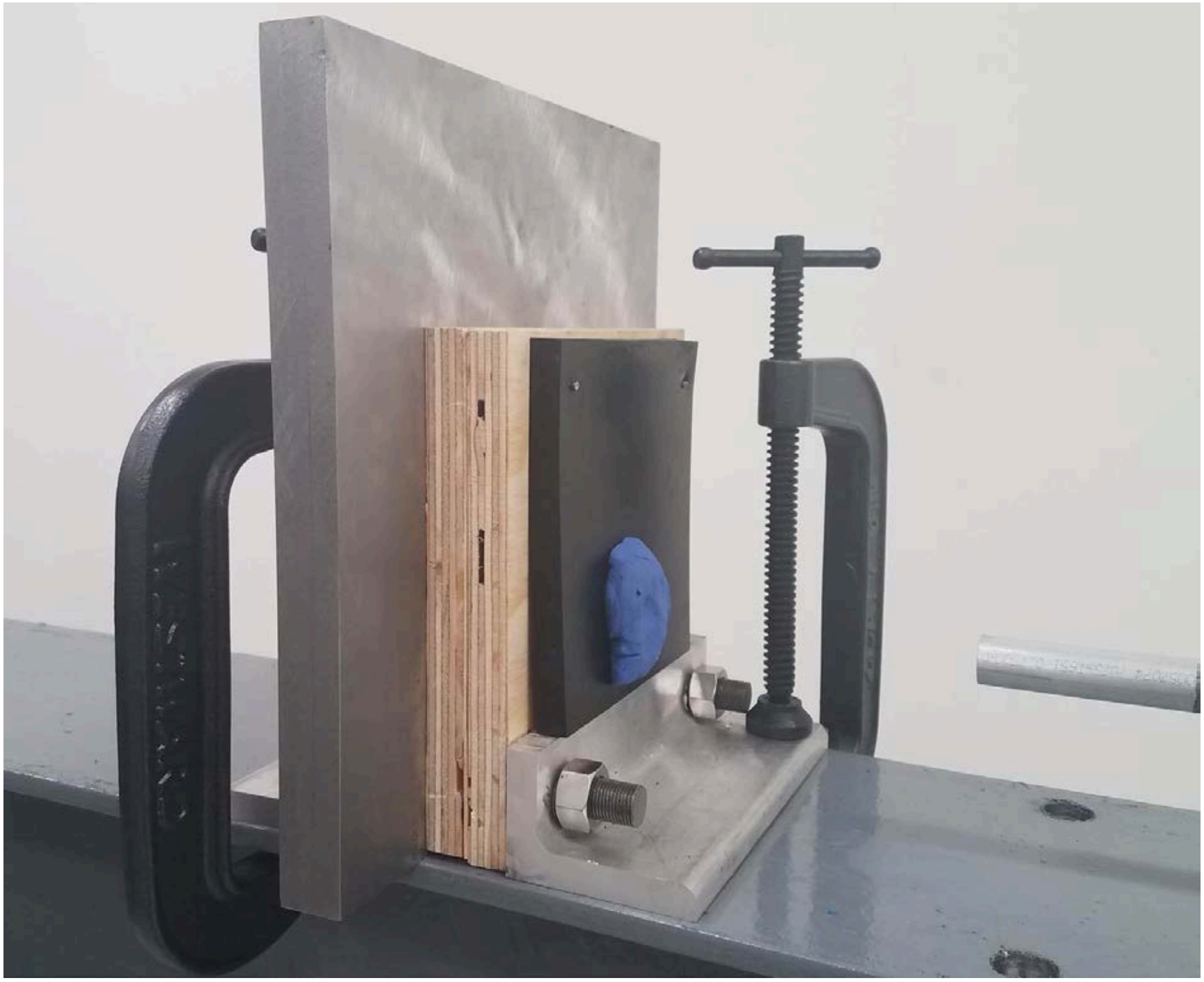


Figure 16. Momentum trap designed for the apparatus.

4. SPLIT HOPKINSON BAR CHARACTERISTICS

After construction, the apparatus was tested for alignment, structural integrity, and experimental repeatability. A laser diode was used to ensure perfect alignment of the pressure bar and the gas gun to ensure linearity. While strain gauges were not attached, several test firings of the projectile were done to create a pressure versus velocity profile for the gas gun. Figure 14 shows the velocity profile from test firing as well as the theoretical curve for a given pressure in the gas gun canister. The theoretical curve for the pressure vs. velocity curve was determined by Eq. 12 below [11]:

$$\begin{aligned} P\forall^{\gamma} &= (0.5)mv^2 \\ P\forall^{\gamma} &= const \\ \gamma &= C_p / C_V \end{aligned} \tag{14}$$

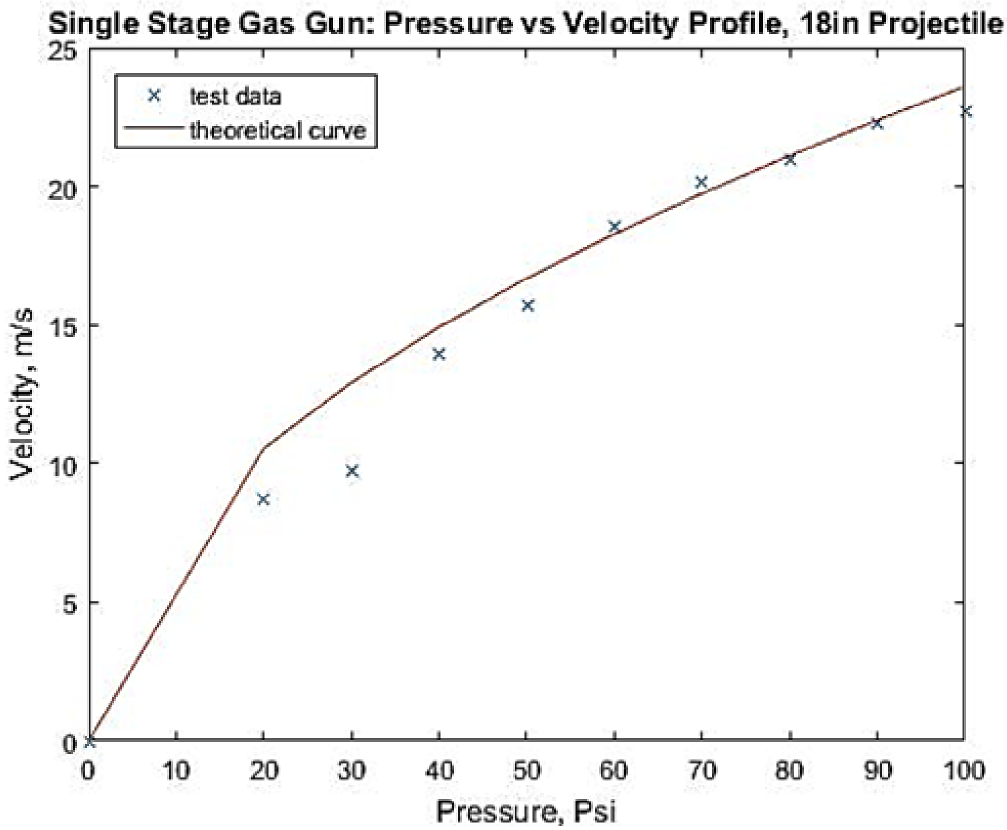


Figure 17. Graph of theoretical data verse experimental data obtained from MATLAB©

The data points were created with the use of the 18 in 7075-T651 aluminum. The volume of pressure chamber was found to be approximately 269.26 in^3, and the mass of the projectile was about 1.09 lbs. While the gas gun is rated to shoot at 100 m/s, smaller projectile lengths will have higher velocities for a given tank pressure. Meanwhile heavier projectiles, such as those made from the Maraging 350 steel will have much lower velocities for a given pressure due to its higher density.

The projectile lengths were determined from literature review. The striker bar is generally less than or half as long as the incident bar to avoid the overlap of the incident and the reflected pulses. Hence, three sizes for projectiles were chosen for this project: 18 in, 12 in, and 6 in. Based on the striking velocity, v_{st}, the incident pulse and strain can be calculated by,

$$\sigma_I = (0.5)\rho_B C_B v_{st} \tag{15}$$

$$\varepsilon_I = (0.5) v_{st} C_B^{-1} \tag{16}$$

Following the equations outlined in the literature review, the strain deformation in the specimen can then be evaluated and a stress-strain time history can be created.

4.1. Single Stage Gas Gun

The original design of the gas gun would have worked just fine compared to the final design however it would have been much harder and more expensive to machine. Originally the end plates of the canister were supposed to be end caps and they were to be threaded onto the canister. The machinists contacted were not able to do this kind of threading along such a big cylinder. A redesign was needed in order for this to be properly machined and the final design had changed to plates on either end of the canister instead of the end caps. Four tie rods were used in order to hold the plates tight against the canister in place of the threads.

Several previous reports recommended using a projectile length equal to half the length of the transmission bar. For this project, that length came out to 18 inches and other projectiles were cut to lengths of 12 and 6 inches. This was done in order to achieve higher speeds necessary for some tests. The projectiles needed to be aligned so support rings called “sabots” needed to be press fitted along the projectiles.

4.2. List of Components and Costs

Throughout the entire design process, potential designs were evaluated by practicality, functionality and cost. In many instances designs were eliminated due to cost. To fabricate the SSGG, there were many issues with finding a vendor to do it not just with a reasonable price, but also be able to fabricate all the parts at once. One company, Zero Hour Parts, a company based in Michigan, that has been used before by this lab was not able to machine the barrel or canister. What they could machine was $3,920. Advanced Manufacturing was able to do the barrel and canister for $4,830. However, WPI Professor Linn was able to do the entire assembly for $5,501. Initially the budget determined by the group was set at $15,000. Table 2 shows the price of all components involved in the final SHPB apparatus. The total price of the components with the added cost of the gas gun manufacturing comes out to $12,520.42 which is below the budget. As mentioned before, the major cost reductions came from using off-the-shelf materials. Minimizing purchase of stock materials and machining unique parts significantly reduced unnecessary costs.

Table 2. Price of all SHPB Components

Category	Vendor	Part Number	Part Name	Qty	Unit Price (USD)	Total Price (USD)
Gas Gun						
Valves						
	Swagelok	SS-8-TA-7-4	Stainless Steel Swagelok Tube Fitting, Female Tube Adapter, 1/2 in. Tube OD x 1/4 in Female NPT	3	13.77	41.31
	Swagelok	SS-810-4	Stainless Steel .5" Union Cross	1	60.28	60.28
	Swagelok	SS-8-TA-1-8ST	Stainless Streel Male Tube Adapter, .5" Tube OD x 3/4-16 Male SAE/MS Straight Thread	2	14.28	28.56
	Swagelok	SS-4P-4M-TFE	316 Stainless Steel Purge Valve, 1/4 in. MNPT, PTFE Ball	1	23.9	23.9
	Swagelok	SS-8-TA-1-8	Stainless Streel Swagelok Tube Fitting, Male Tube Adapter, 1/2" Tube OD x 1/2" Male NPT	2	13.57	27.14
	Swagelok	SS-810-6	Strainless Steel Swaglok Tube Fitting, Union, 1/2" Tube OD	1	23.97	23.97
	Swagelok	SS-810-3	Strainless Steel Swaglok Tube Fitting, Union Tee, 1/2" Tube OD	1	45.8	45.8
	McMaster-Carr	400K549	Multipurpose Guage, Steel Case, Dual, 2" Dial, 1/4 Bottom Connection (rated for 0-600 psi)	2	10.15	20.3
	McMaster-Carr	4440K124	High-Flow Muffler, 1/2 NPT Male, 280 Maximum scfm. 6" Height	1	13.62	13.62
	McMaster-Carr	6534K73	Industrial-Shape Hose Coupling, Size 3/8, Zinc-plated Steel Plug, 1/2 NPTF Male End	1	4.62	4.62
	McMaster-Carr	4627K213	Medium-Pressure Iron Pipe Fitting 90 Degree Elbow Connector, 1/2 NPT Female	1	10.4	10.4
	McMaster-Carr	4830K171	Standard-Wall 304/304L Stainless Steel Pipe Nipple Fully threaded, 1/2 Pipe Size	1	2.18	2.18
	BuyJamesbury	9FB3600XTB	1/2" Jamesbury Eliminator Series Ball Valve	1	45	45
Internal components						
	McMaster-Carr	93839A031	Zinc Yellow-Chromate Plated Steel Thin Hex Nut, Grade 8, High Strength, 3/8"-16 Thread Size	1	9.39	9.39
	McMaster-Carr	93839A030	Zinc Yellow-Chromate Plated Steel Thin Hex Nut, Grade 8, High Strength, 5/16"-18 Thread Size	1	7.55	7.55

	McMaster-Carr	6436K23	Clamping Two-Piece Shaft Collar for 1-1/2" Diameter, Black-Oxide 1215 Carbon Steel	3	8.63	25.89
	McMaster-Carr	9452K192	Oil-Resistant Buna-N O-Ring 1/8 Fractional Width, Dash Number 242	1	11.29	11.29
	McMaster-Carr	9452K41	Oil-Resistant Buna-N O-Ring 1/8 Fractional Width, Dash Number 220	1	10.04	10.04
	McMaster-Carr	9452K116	Oil-Resistant Buna-N O-Ring 1/16 Fractional Width, Dash Number 029	1	8.49	8.49
	McMaster-Carr	91251A734	Black-Oxide Alloy Steel Socket Head Screw 1/2"-13 Thread Size, 5-1/2" Long	4	2.79	11.16
	McMaster-Carr	95036A039	Extreme-Strength Steel Hex Nut Grade 9, Cadmium Yellow-Chromate Plated, 5/8"-18 Thread Size (5 Pack)	2	9.35	18.7
	Lee Spring	LC-063G-12 M	LC-063G-12 M	1	6.8	6.8
Oscilloscope and Electronics						
	Newark	MDO 3024	OSCILLOSCOPE, 4-CHANNEL, 200MHZ, 2.5GS/S; Product Range:MDO3000 Series;	1	3442.5	3442.5
	Mouser Electronics	AD8024ARZ	High Speed Operational Amplifiers Quad 350MHz 24V	1	8.79	8.79
	McMaster-Carr	90303A135	Nylon-Tip Socket Head Screw 1/4"-20 thread size, 1" long	15	3.27	49.05
	Texas Instruments	INA126E/250	INA 126 Micropower Instrumentation Amplifier Single and Dual Versions	1	4.54	4.54
	Texas Instruments	INA128P	INA128, Precision, 130-dB CMRR, 700-µA, Low-Power, Instrumentation Amplifier	1	11.57	11.57
Sabot						
	McMaster-Carr	8576K23	Black Delrin ® Acetal Resin Rod 1-1/4" Diameter 1 Ft	2	7.37	14.74
Split Hopkinson Pressure Bar						
Platform Support						
	Sullivan Metals	WF831	Wide Flange Beam 8"X10' (620 lbs)	2	219.61	439.22
	McMaster-Carr	92620A752	Zinc Yellow-Chromate Plated Hex Head Screw, Grade 8 Steel, 1/2"-20 Thread, 4" long, fully threaded	50	6.04	302

	McMaster-Carr	98023A033	Zinc Yellow-Chromate Plated Grade 8 Steel Washer for 1/2" Screw Size, 0.531" ID, 1.062" OD (25 Pack)	4	6	24
	Sullivan Metals	ST22316	Square Tube 2"X2"X3/16" cut to 2'	12	6.87	82.44
	Sullivan Metals	ST22316	Square Tube 2"X2"X3/16" cut to 2'	6	7.54	45.24
	McMaster-Carr	8910K709	Low-Carbon Steel Rectangular Bar, 1/2" thick, 4" width, 1' length	10	25.65	256.5
	McMaster-Carr	8910K643	Low-Carbon Steel Rectangular Bar, 5/16" thick, 6" width, 1' length	2	32.24	64.48
	McMaster-Carr	60855K55	Heavy Duty Vibration-Damping Leveling Mount with stud, 1/2"-13 thread, 600lb max load	20	7.65	153
	McMaster-Carr	92196A583	18-8 stainless steel socket head screw 5/16"-18 Thread size, 1" long, packs of 25	1	10.04	10.04
	McMaster-Carr	94895A825	High Strength Steel Hex Nut Grade 8, Zinc Yellow Chromate plated, 1/2"-20 thred size, packs of 50	2	8.2	16.4
	Lowes	86511	Rust-Oleum Professional Smoke Gray Gloss Enamel Interior/Exterior Paint (Actual Net Contents: 32-fl oz)	2	9.58	19.16
	Home Depot	2081830	12 oz. Flat Light Gray Automotive Primer Spray Paint	5	3.76	18.8
	Grainger	2FAA7	Square stock Aluminum 6061, width: 1.75", thickness: 1.75", length 72"	1	137.15	137.15
	McMaster-Carr	1865K7	Easy Access Base Mounted Shaft Support for 1-1/4" shaft diameter, 6061 Aluminum	9	31.6	284.4
Catchment System						
	Grainger	2LAY7	Regular Duty Cast Iron C-Clamp, 6" Max. Opening, 2-3/4" Throat Depth, Gray	4	12.88	51.52
	Grainger	35X905	Modeling Clay Assortment	2	5.68	11.36
	Home Depot	N/A	Plywood, 24" x 24", 1/2 thick	1	8.27	8.27
Pressure Bars						
	MSC Direct	64401342	1.25 in Diameter x 36 in Long, Aluminum Round Rod, Alloy 7075	2	86.52	173.04
	MSC Direct	64401284	3/4 in diameter x 72 in Long, Aluminum Round Rod, alloy 7075	1	62.88	62.88

SSA	N/A	MAR350 RD MIL-S-46850 T/4 CGA 3/4" Dia. x. 72"	1	387.5	387.5
SSA	N/A	MAR350 RD MIL-S-46850 T/4 CGA 3/4" Dia. x. 36"	1	200	200
SSA	N/A	MAR350 RD MIL-S-46850 T/4 CGA 3/4" Dia. x. 24"	1	175	175
MSC Direct	34401433	3/4 in diameter x 36 in Long, Aluminum Round Rod, alloy 7075	3	36.48	109.44
		Total			7019.42

5. CONCLUSIONS AND RECCOMENDATIONS

The SHPB apparatus and SSGG designed and constructed during this project meets the constraints necessary in order to conduct successful impact tests on materials to be used in the aerospace industry. These constraints include the ability to accommodate different pressure bars as well as having an adjustable alignment system to ensure the accuracy of the experiment. This apparatus is versatile with its range of alignment as well as size of pressure bars in both length and diameter through the use of the various support features discussed in this paper with an emphasis on the shaft collars, mounting blocks, and leveling feet. These features enable this apparatus to be used with different pressure bars allowing for a range of tests on materials to be completed by maintaining the accuracy and structural integrity of the entire system.

In order to further develop the project, proper electronics, alignment method, and bars of different materials are required to measure certain properties. The electronics consist of the amplifier circuits to amplify the output voltage of the strain gauges to be put on the SHPB. One must be careful in the selection of the amplifier because there can be a lot of unnecessary noise amplified. There is a certain amount of tradeoff between the gain and noise reduction of the amplifier. A gain of about 100 while keeping noise low is ideal when choosing an amplifier. The strain gauges to be used are ⅛ inch long and have a resistance of 350 Ohms however others can be used if applied properly. Alignment remains an issue and it is critical to make sure that the apparatus is totally aligned before every experiment. A way to help with this issue would to add a more permanent laser alignment system to ensure that the apparatus maintains perfect linearity. Finally, bars of different materials allow for a wider range of materials that can be tested in the Split Hopkinson Pressure Bar.

APPENDICES

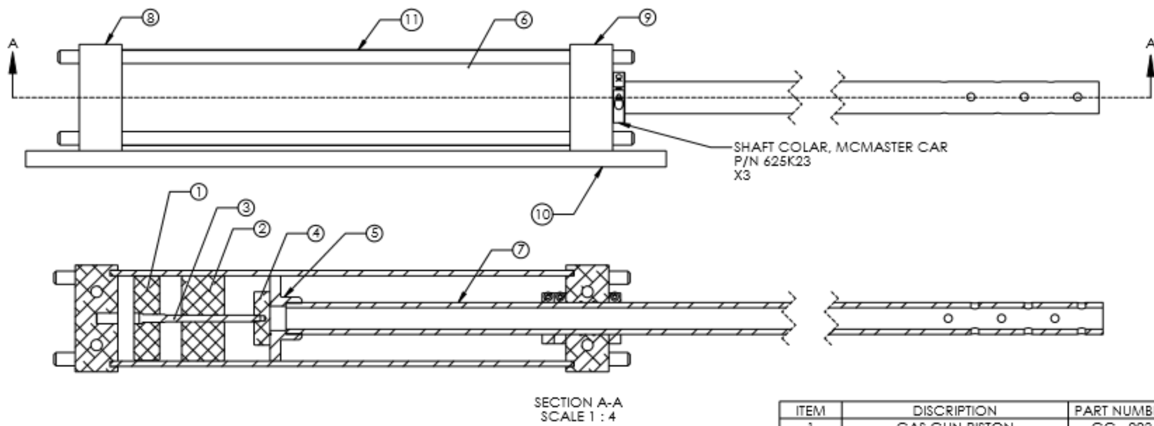
Appendix A Gas Gun Operation Manual

OPERATION

1. Check to ensure safety:
    a. Gun is bolted down,
    b. Pointed at the intended target, and
    c. No one is near the sample
2. Open the bleed valve to ensure no pressure in the gun.
3. Ensure the inlet and outlet ball valves are closed.
4. Connect the Gas Gun to the compressor (that has a regulator), to the quick connect valve adapter (connected to the inlet ball valve).
5. Close bleed valve.
6. Check the pressure reading of the compressor and make sure it is above the desired outlet pressure. Also check the regulator reading. This becomes increasingly important if firing multiple times.
7. Reopen the bleed valve.
8. Load desired projectile into the barrel, after applying a light cover of grease to the outer diameter of the sabots.
9. Push the projectile into the barrel (can be done with incident bar) until slight resistance is felt.
10. Re-check that the outlet ball valve is closed.
11. Close bleed valve.
12. Open inlet ball valve, slowly. If done too fast a pressure difference will be created prematurely firing the gun.
13. Check the two valves on the gas gun to make sure they are at desired pressure.
14. If pressure is correct, close inlet ball valve.
15. Preform quick safety check.
16. Quickly open the outlet ball valve.
17. Close outlet ball valve.
18. Repeat steps 7-17 for another test.
19. When tests are completed:
    a. Open bleed valve
    b. Remove projectile from barrel
    c. Disconnect the gas gun from the compressor.
    d. Close both ball valves.
    e. Close Bleed valve.

ASSEMBLY

*Please note, it is recommended to have at least 2 people assemble the gas gun.



ITEM	DISCRIPTION	PART NUMBER	QTY.
1	GAS GUN PISTON	GG - 003	1
2	GAS GUN GUIDE, VALVE	GG - 004	1
3	GAS GUN PIN, VALVE	GG - 005	1
4	GAS GUN PLATE, VALVE	GG - 006	1
5	GAS GUN SUPPORT	GG - 007	1
6	GAS GUN TUBE	GG - 008	1
7	GAS GUN BARREL	GG - 009	1
8	GAS GUN CAP, RELEASE END	GG - 010	1
9	GAS GUN CAP, BARREL END	GG - 011	1
10	GAS GUN PLATE, MOUNTING	GG - 012	1
11	GAS GUN TIE-RODS, MOUNTING	GG - 013	1

Figure A-1: Gas Gun Assembly

1. The Piston (Item 1) screws into the Pin (Item 3), making sure the flat head of the Pin is in the counterbored hole, or recess, of the Piston.
2. Screw on a 3/8” -16 UNC hex-nut onto the remaining threads of the Pin, this is to protect the threads.
3. The Guide (Item 2) slides onto the unthreaded section of the Pin.
4. Fully screw on a 5/16”-18 UNC hex-nut onto the remaining threads.
5. The Valve Plate (Item 4) fully screws into the remaining threads of the Pin.
6. The Lee Spring, LC-063G-12, gets placed in the recess of the Piston. (Figure A-2 shows the progress up to this step)

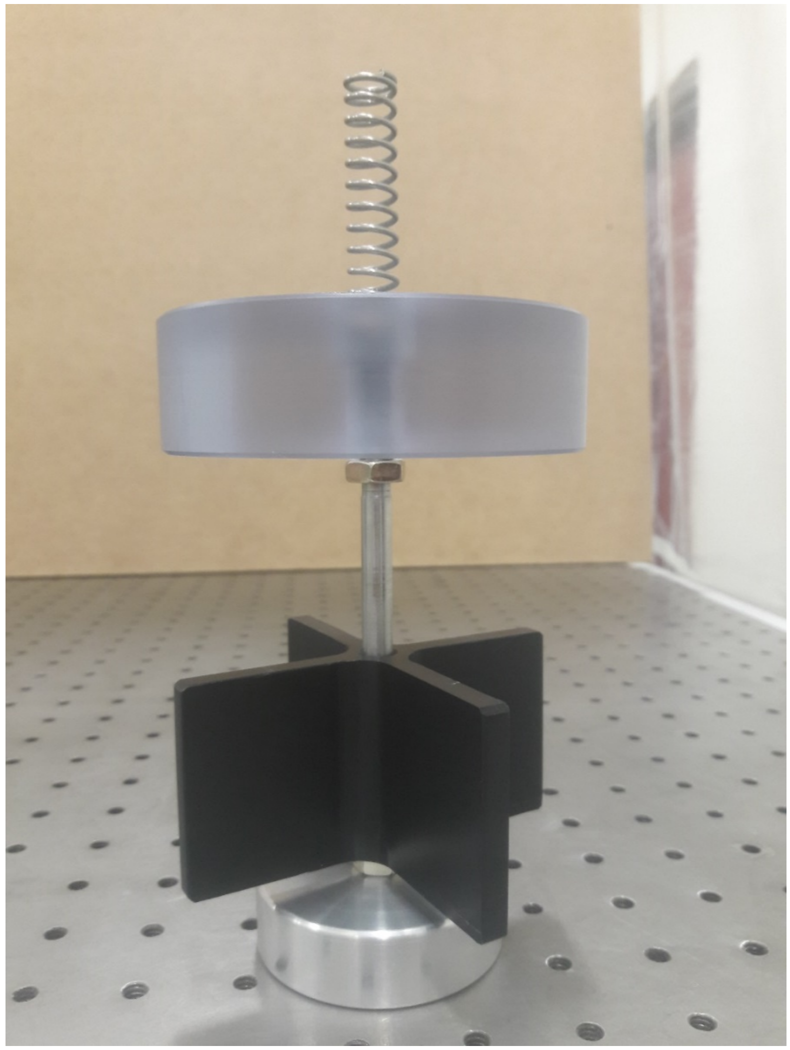


Figure A-2: Assembly Up To Step 6

7. The Support (Item 5) screws into the threaded end of the Barrel (Item 7).
8. The two Shaft Collars going inside canister are placed at right dimension, 13.25” from the threaded end of the barrel. When adding shaft collars, ensure they are on evenly (gaps between two semi circles are equidistant). Figure A-3 shows the progress of steps 7 and 8.

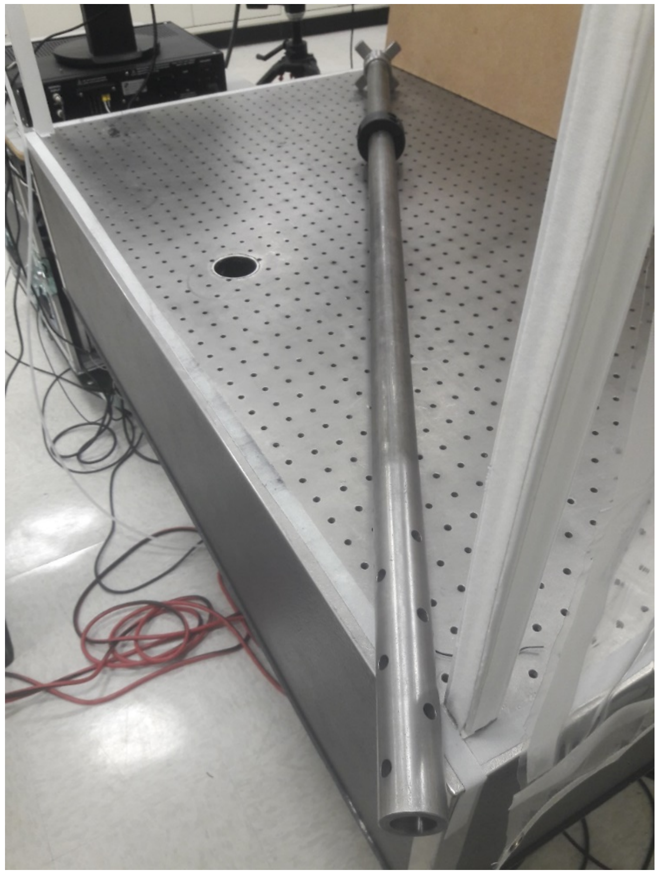


Figure A-3: Steps 7 and 8

9. Insert all 3 O-Rings:
    a. A 1.375” I.D. 1/8” thick O-Ring in groove of the Support
    b. A 4” I.D. 1/8” thick O-Ring in inner grooves (where canister fits in) of each Cap (Items 8 & 9)
    c. A 1” I.D. 1/16” thick in each of the two grooves in the barrel hole in the Barrel End Cap (Item 9)
10. Apply a thin layer of grease (we used Lubriplate) to the inner diameter of the hole of the Barrel End Cap, and the outer diameter of the barrel.
11. The Barrel End Cap slides onto the Barrel until flush with shaft collars. Ensure the grooves face toward the threaded end. This may require some force.
12. Last shaft collar gets placed flush against other end of Barrel End Cap. Assembly up until this point is shown in Figure A-4.

Figure A-4: Assembly from Steps 7-12

13. Grease the inner diameter of the Canister (Item 6).
14. Slide assembly from step 7-12 into the Canister. Ensure the Canister is fully in the groove of the Barrel End Cap.
15. Screw in the threaded inserts into the Mounting Plate (Item 10).
16. Place Release End Cap onto one of the sets of holes on the Mounting Plate, aligning the holes and ensuring the side of the Cap with the Canister groove is facing the other set of holes in the Mounting Plate. Screw in a 5-1/2" long ½"-13 thread (McMaster-Carr P/N: 91251A734) into each of the aligned holes.

17. Insert the assembly made from steps 1-6 into the opposite end of the Canister with the spring end facing out.
18. Slide the assembly made from the previous step, inserting the free end of the Canister into the Release End Cap's groove. Also ensure the spring goes into the recess in the middle of the Cap. Ensure the canister is fully in the groove. Do not worry, the holes on the Cap will not align with the holes in the Mounting Plate. The assembly up until this point is shown in Figure D-5.

Figure A-5: Assembly as of Step 18

19. Slide the 4 Tie Rods (Item 11) through either side of the Caps.
20. Make sure both ends of the tie rods stick out evenly past both of the plates
21. Slide the steel washers on all 8 ends of the Tie Rods
22. Screw on the 8 5/8"-18 UNC nuts over the washers and tighten them until the holes on top of the Barrel End Cap lines up with the holes on the Mounting Plate.
23. Screw in the remaining two 5-1/2" bolts and fasten them tightly.
24. Check for and tighten any loose nuts on the Tie Rods. Figure A-6 shows the full assembly without the valve connections.

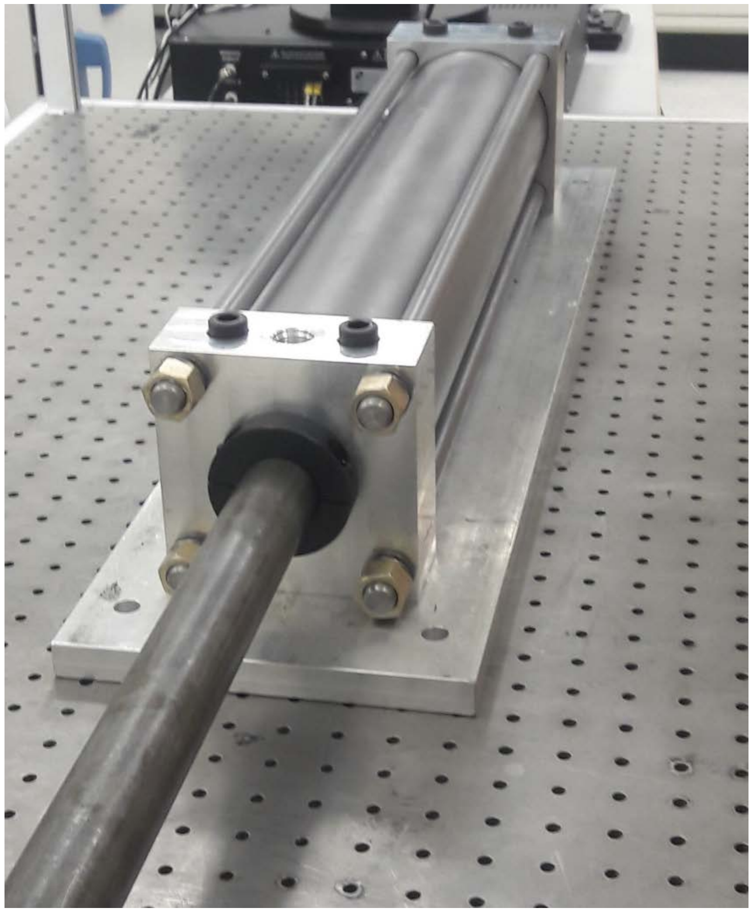


Figure A-6: Complete Assembly without Valve Connections

25. Screw in the union cross into the Barrel End Cap, and appropriate connections (bleed valve, pressure gauge, ball valve with quick connect adapter, and SAE straight connection). See Figure A-7 for diagram with components used for this gun.

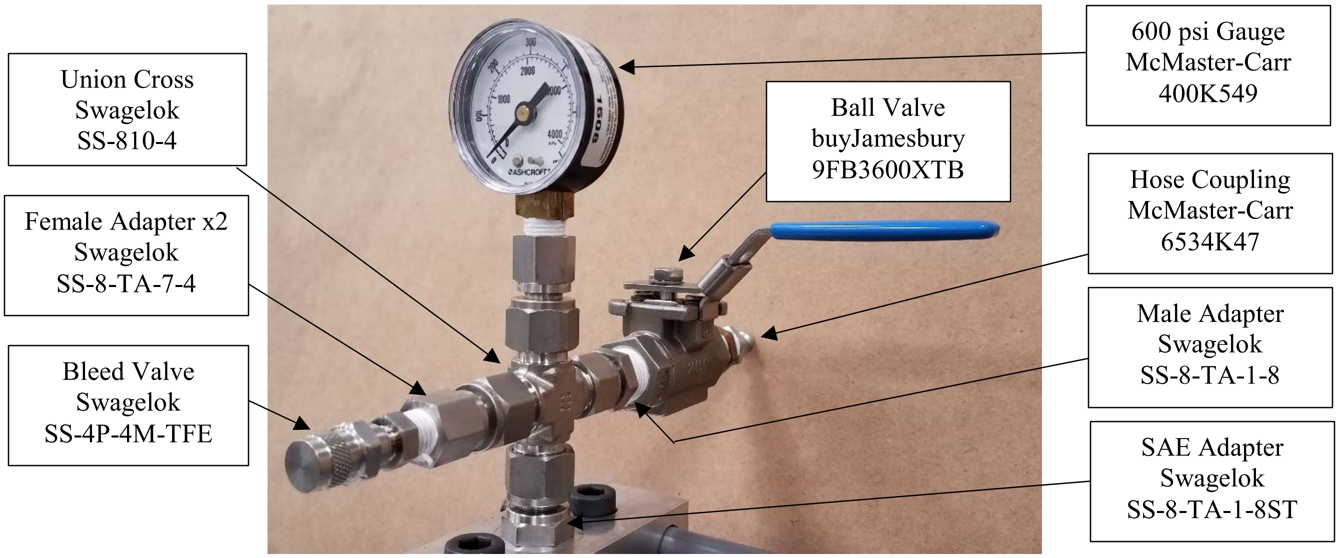


Figure A-7: Inlet Valve Connections (with manufacturers and P/N)

26. Screw in the T-valve in the back of the Release End Cap, and appropriate connections (pressure gauge, ball valve with muffler, and SAE straight connection). See Figure A-8 for diagram with components used for this gun.

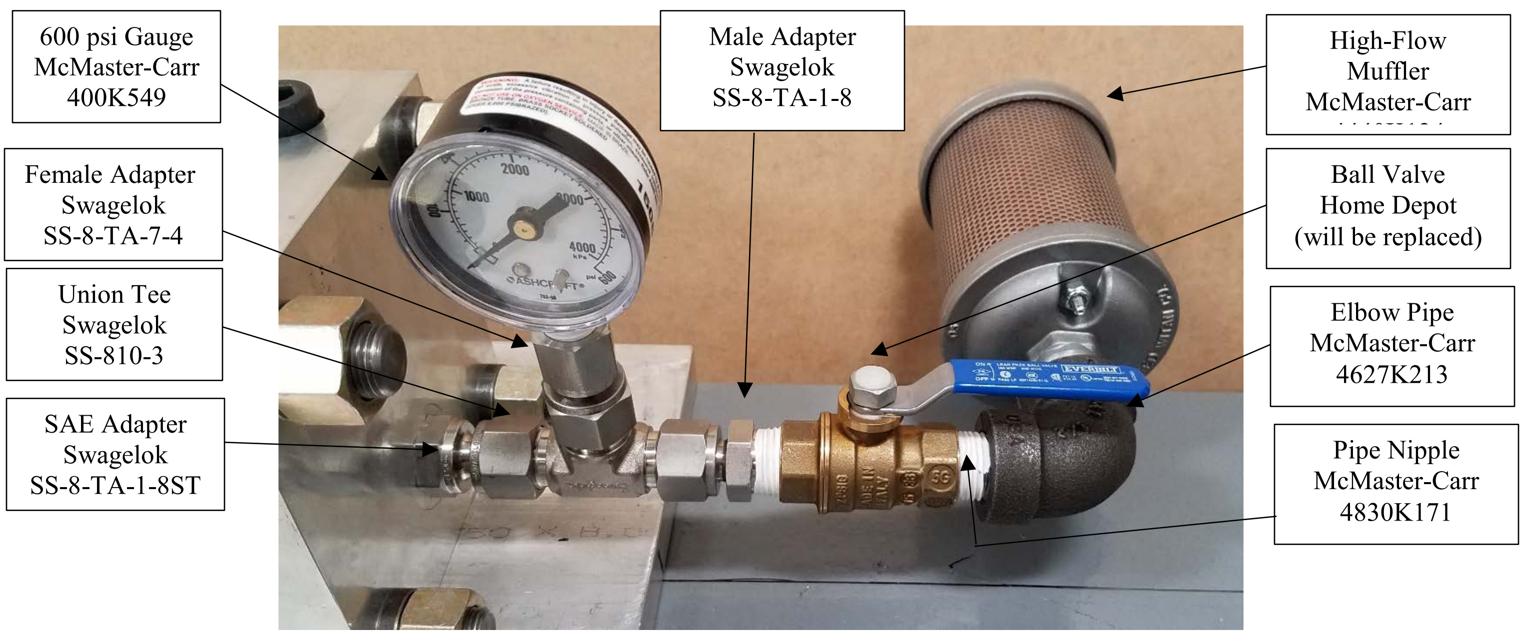


Figure A-8: Outlet Valve Diagram (with manufacturers and P/N)

27. Attach silencer to the end of the back valve in a manner that won't interfere with the base plate or I-Beam
28. Screw on the entire setup onto the I-Beam with washers on both sides then fasten a nut onto the bottom side

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