Executive Summary

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Over the last two years, a miniature Split Hopkinson Pressure Bar system has been designed and constructed to investigate properties of thermoplastic materials under dynamic loading conditions at variable, high strain rates. The designed system will be 4m in length, cost $7000 and operate in the strain rate regime of 1000 - 5000 s^{-1}.

MOTIVATION

Tensile, bending, and torsion tests are some of the most iconic tests in materials science and engineering used to characterize materials. What each of these testing methods have in common is they slowly apply a load to a specimen to evaluate stresses and strains developed. While these tried-and-true testing methods provide great accuracy in describing material properties under pseudo-static, low strain rate loading conditions, a material's properties drastically change under more dynamic, high strain rate, loading. Therefore other tests are needed to characterize materials for these loading conditions. Strain rate is the measure of how fast a material strains due to some applied stress and has units of s^{-1}; bomb explosions, ballistic impacts and car crashes are all examples high strain-rate loading and material tests are needed to fully understand the mechanics of these events.

A Split Hopkinson Pressure Bar (SHPB) is a testing apparatus used to characterize the dynamic stress-strain response of materials. The SHPB was developed in 1914 by Bertram Hopkinson to measure stress pulse propagation in a metal bar and was modified by Herbert Kolsky in 1949, using two Hopkinson Bars in series, to measure stress and strain for compression, tension, and/or torsion testing at high strain rates. A SHPB system is shown below in Figure 1 consisting of a gas gun, striker bar, incident bar, transmission bar, momentum trap, sample, and data acquisition system.

Typically, SHPB systems only achieve strain rates in the order of $100s^{-1}$ but through a thorough analysis of SHPB literature and theory, our group has designed a system to evaluate materials at strain rates of 1000 – 5000s^{-1}; This is done by miniaturizing the system, making our total system length 4m compared to typical 10m long systems. Additionally, SHPB systems are typically designed to characterize metal materials, but our goal is to investigate the response of low mechanical impedance materials such as polymers. Over the last two years, a miniature Split Hopkinson Pressure Bar system has been designed and constructed to investigate properties of thermoplastic materials under dynamic loading conditions at variable, high strain rates.

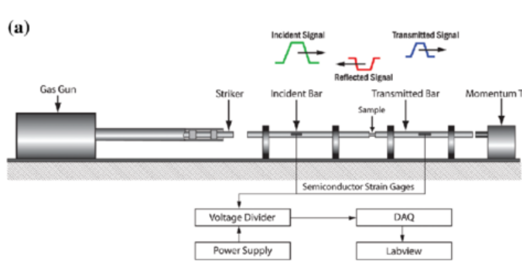

FIG. 1. Diagram of Typical Split Hopkinson Pressure Bar System

DESIGN AND CALCULATION

The general operating procedure of a SHPB is as follows: First, a small cylindrical material sample is sandwiched in between the incident and transmission bars as shown in Figure 1. The striker is then accelerated by the gas gun to impact the incident bar which sends a one-dimensional stress wave, known as the "incident wave" down the incident bar and into the sample. Due to an impedance mismatch between the incident/transmission bar material and the sample, part of this stress wave is reflected off of the sample back into the incident bar and is known as the "reflected wave" while another part of the wave is absorbed by the sample. The part absorbed by the sample again splits into two due to impedance mismatches: one part reflects and disappates within the sample and the other travels into the transmittance bar and is known as the "transmission wave". Throughout the test, synchronized high sensitivity strain gauges placed on the incident and transmission bars measure the amplitude of the incident, reflected and transmission waves as shown in Figure 3. This data with the other parts of the data acquisition system are then used to generate a characteristic strain rate curve for a given material. The momentum trap at the right of Figure 1 simply arrests the motion of the system. In the following subsections, the design considerations for each part of the system will be described.

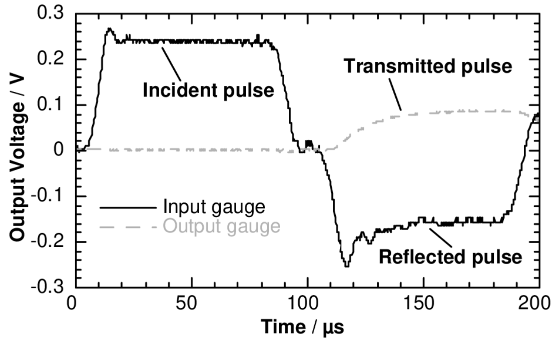

FIG. 2. Typical plot generated by SHPB strain gauges

Bar Material, Length, and Striker Velocity Requirements

Each SHPB system is designed for a certain set of operating conditions, so the first step in system design was to define the desired sample material and strain rate regime on which to use the SHPB. As described in the motivation section, the system is to be used to characterize polymer materials at high strain rates (1000 - 5000 s^{-1}).

With these goals set, the bar size and material could be chosen. As shown in Figure 3, the intensity of the transmitted wave is very weak, so it is imperative to select a bar material with similar mechanical impedance to the specimen of choice to maximize the transmittance. Aluminum 6061 was selected as the bar material due to its mechanical impedance being most similar to polymers compared to other metals. Additionally, metal bars were chosen due to their high compressive yield strength, low cost, and ease of stress-strain back calculation. Polymer bars were considered for impedance matching purposes, but its lower yield strength would have decreased the operating strain rate regime since the system needs to operate in the bars' elastic regime for longevity.

The next significant parameter to determine is the striker length which is fixed based on the maximum test duration calculated according to the maximum expected deformation at lowest design strain rate the system is capable of given in Equation 1

$$\Delta T = \epsilon_{max}/\dot{\epsilon}_{min} \tag{1}$$

where ΔT is the maximum test duration, ϵ_{max} is the maximum design strain and $\dot{\epsilon}_{min}$ is the minimum design strain rate.

How does test duration relate to the length of the striker? Another way to think about the test duration is as the duration of the incident pulse imparted by the striker to the incident bar. When the striker impacts the incident bar, the incident wave propagates down the incident bar, and continues being generated until the striker and incident bar separate from one another. While the incident wave is generated upon striker impact, another wave is sent back down the striker toward the gas gun. When this reflected wave reaches the gas gun end of the striker it reverses direction and travels back toward the incident bar. Once the striker reflected wave reaches the incident bar side of the striker again, the striker and incident bar separate and the incident wave ceases being generated. Figure **??** shows a diagram of the incident pulse generation for clarity.

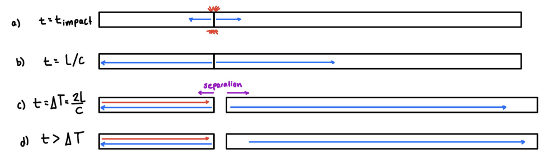

FIG. 3. Diagram of incident pulse generation

With this understanding of how the stress wave propogates through the striker bar, one can start to see how the striker length is related to the maximum test duration. Equation 2 below gives this relationship between striker length and maximum test duration.

$$L_{st} = \Delta T \frac{C}{2} \tag{2}$$

where L_{st} is the striker length, and C is the wave speed in the striker bar material. It is shown that the duration of the test is the time it takes for the stress wave to travel the length of the striker twice.

From the striker lengths, the incident and transmission bar lengths can be calculated. Since the bar material is the same as the striker material, the *size* of the stress wave can be viewed as either the duration of the stress wave or equivalently, two times the length of the striker. The incident, transmitted, and reflected strain gauge signals need to be isolated during the strain measurement, so it is imperative that the incident and reflected waves do not superimpose on one another at the stain gauge location. As a result, the incident and transmission bars each need to be at least twice as long as the longest striker bar since the strain gauges will be mounted in the middle of each.

This is the working theory behind SHPB bar size selection. We also had a design constraint that the system would be less than 4m long, so this also came into play when designing the system. As a result, the incident and transmission bar lengths were set to be 1250mm each while the striker was set to be 500mm. By massaging Equations 1 and 2 one can see that a higher strain rate is achieved with a shorter bar, so a 250mm bar was also manufactured for higher strain rate testing. The 500mm striker yields a ΔT of 196 μs while the 250mm bar yields a ΔT of 98 μs and with an anticipated maximum strain rate of 1, the minimum achievable strain rates are 5091 and 10182 s^-1 for the 500mm and 250mm strikers respectively.

With the choice of an aluminum striker, the maximum striker impact speed was also determined. The stress developed from the striker impact is given below by Equation 3

$$\sigma_{dev} = \rho c v_{st} \tag{3}$$

where σ_{dev} is the developed stress, ρ is the material density, c is the wave speed and v_{st} is the striker impact velocity. Rearranging equation 3 for v_{st} and plugging in the yield stress, wave speed, and density of Al-6061 (276MPa, 5091m/s, and 2.7g/cm^3 respectively) yields a maximum striker design velocity of 20.1 m/s. Since the system needs to operate completely in the elastic regime, the aluminum strikers will only ever be accelerated to 15m/s.

This design striker velocity will be used later for the calculation of the gas gun parameters, and the energy capacity of the momentum trap.

One-Dimensional Waves and Bar Alignment

One of the most important parts of SHPB theory is that the stress wave produced is one-dimensional. This means that the produced stress wave is axisymmetric, travelling uniformly down the bar axis with no radial velocity component. The one-dimensional wave assumption is crucial to the calculation of stress and strain rate in SHPB theory; This is what allows the material stress and strain rate to be calculated by measuring the reflected and transmitted waves.

A perfect one dimensional wave cannot exist: while the bar material is displaced by the primarily axial stress wave, there is also a radial displacement within the bar due to Poission's effects. This is called dispersion and is needs to be minimized through careful system design. Dispersion effects become more significant as the bar diameter increases but are negligible if the ratio of bar length to diameter is greater than 20 as described by Equation 4

$$\frac{L_b}{D_b} > 20 \tag{4}$$

where L_b and D_b are the bar length and diameter respectively. With the length of the bars set to be 1250mm, the bar and striker diameter was chosen to be 20mm.

With this, all the critical dimensions of the strikers are set, so the energy capacity requirement of the momentum trap can be calculated. The shock absorber needs to be able to absorb the kinetic energy of the largest striker travelling at the maximum design velocity. The maximum kinetic energy of the system is given by equation 5

$$KE_{max} = \frac{1}{2} m_{st} {v_{st}}^2 \tag{5}$$

where m_{st} is the largest striker mass of .424kg (the density of aluminm times the 500mm striker volume) and v_{st} is the fastest striker impact velocity of striker, 15m/s. With this, the energy capacity was calculated to be 95.4 joules and a momentum trap was selected accordingly.

Returning to the one dimensional wave discussion, the bar geometry is only one part of ensuring the propagation of a one dimensional wave. Another significant parameter is the axial alignment and levelness of all the system components which starts from the ground up in system design. Initially, an optical breadboard table was considered to ensure precise alignment of the system, but this idea was abandoned due to cost and extensive lead times. The use of an I beam was also considered to align the components but was also abandoned due to lack of tight tolerancing. Eventually, a table made from 8020 aluminum extrusion was designed to support the entire system and was fitted with adjustable feet to ensure the levelness of the system.

To ensure the axial alignment of the bars, an adjustable alignment system consisting of many adjustable triangular supports was designed. Two 4m long, 50mm diameter steel alignment bars with a straightness of at least .25mm/1000mm were mounted to the aluminum extrusion table making use of shaft block clamps. Several triangular aluminum supports, shown in Figure 4, were machined and fitted with low friction bearings in their upper holes. These supports slid onto the alignment bars and were locked into place making use of several threaded screw holes on the sides. The gas gun barrel, incident bar, and transmission bar were all inserted into the support bearings and their alignment can be finely tuned via the screws which dictate how the supports sit on the straight, steel alignment bars.

With the system mostly aligned, only a few more considerations had to be made to enable the use of the one dimensional wave assumption. First, the bars needed a face perpendicularity of $\pm$.03deg and a straightness of $<$.25mm/1000mm, two conditions met by the bar manufacturer. The faces of the bars also needed to be smooth to ensure direct bar contact, so additional machining was done to ensure a good surface finish.Two PTFE sabots were fixed to each striker to reduce friction and ensure axial alignment between striker and the incident bar as the striker travels through the barrel.

With these considerations the one dimensional approximation can be made and the SHPB theory can be used. From a visual inspection, the bars look very aligned as shown in Figure 5 and once the data

FIG. 4. Machined Traingular Bar Alignment Supports

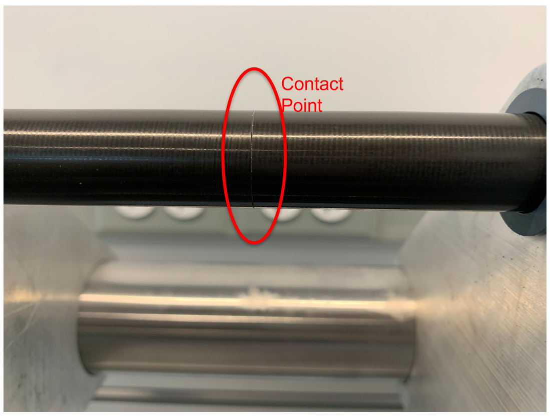

FIG. 5. Contact point of incident and transmission bar in actual setup to evaluate alignment

acquisition system is configured, the alignment can be systematically verified by running the system without a specimen and evaluating the incident and transmitted wave forms.

Samples

Like other material tests, the American Society for Testing and Materials (ASTM) has published specifications for the samples used in a Split Hopkinson Pressure Bar system. Just as a tensile test has a characteristic dogbone shape sample and a Charpy impact test has its notched bar, the SHPB test has a flat cylinder.

The actual dimensions of these cylindrical samples are primarily determined by other system parameters to maximize the transmitted signal and minimize losses due to dispersion. The sample diameter is determined by the ratio in Equation 6

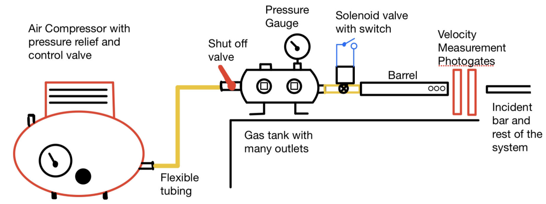

FIG. 6. Schematic of Gas Gun System

$$\frac{D_b}{D_s} = 2 - 3 \tag{6}$$

which says the ratio of bar diameter to sample diameter should be somewhere between 2 and 3. This ensures the transmitted wave is in the finite strain regime for ease of strain data collection.

The length of the sample is then determined by the chosen sample diameter to minimize dispersion to maintain one dimensional of the stress wave. Equation 7 describes the relationship between sample length and sample diameter

$$\frac{L_s}{D_s} = 0.6 - 1 \tag{7}$$

With this condition satisfied, radial inertia and spreading friction effects in the sample will be minimal. It is also important to have such a short sample to avoid barreling which would also effect the calculated strain.

From these conditions, the samples can have a diameter of 15mm and a length of 9mm to 15mm. A mold will have to be machined to these specifications to rapidly produce consistent polymer samples of this geometry.

Gas Gun

As described in the operation overview of an SHPB system, the stress wave is produced by a striker accelerated by a gas gun impacting the striker bar. A schematic of the gas gun is shown in Figure 6 and consists mainly of a tank of pressurized air, a solenoid release value, and a barrel.

As described above, the design requirement for the gas gun is that it must accelerate the longest aluminum striker to 15 m/s for impact with the incident bar. This parameter dictates the pressure which gas gun needs to be designed to accommodate since pressure in the air tank is what will accelerate the bar. Manipulating Newton's second law and a kinematic equation for the striker acceleration, along with relevant geometry, a relationship between tank pressure and impact velocity was derived in Equation 8

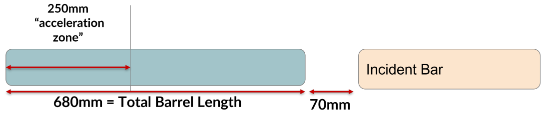

FIG. 7. Schematic showing acceleration length calculation

$$P = \frac{V_{st}^2 m_{st}}{2A_{st}L_c} \tag{8}$$

Where P is pressure, V_{st}, m_{st}, A_{st} are the striker velocity, mass, and area (including sabots) respectively, and L_c is the length the striker can accelerate before impacting the incident bar, and is determined by striker length and the system geometry.

As shown in Figure 7, the barrel length was chosen to be 680mm, with its end 70mm away from the incident bar to keep the total system length right at 4m. For the 500mm striker, this yields an acceleration length of 250mm.

Plugging in the known 500mm aluminum striker mass and cross section area with sabots, the maximum pressure the system needs to withstand was calculated to be 40 PSI gauge. With an additional factor of safety of 3, all the components were designed to withstand up to 120PSI.

Based on this design pressure, the barrel and other components were selected. A thin-walled pressure vessel calculation was carried out for the barrel to determine the barrel thickness and material to avoid it from bursting. Although during acceleration the barrel is a thin walled pressure vessel, the design pressure is relatively low and for both an aluminum and steel barrels the required barrel thickness is <.025mm from this calculation. As a result, the barrel thickness was selected to be 2mm due to availability of stock parts. The barrel had several slots machined into the end to allow air to escape from in front of the striker. As the striker travels down the length of the barrel, it displaces air and without these holes an "air cushion" could develop in front of the striker and blunt its impact.

All other gas gun components were selected with this 120PSI design pressure in mind. A steel tank rated up to 200 psi was selected and fitted with a pressure gauge, shut off valve, and a nominally closed solenoid valve which screws directly onto the barrel. The solenoid valve is powered by 24V wall adapter and is actuated via a switch. The tank is pressurized by an air compressor with a built in regulator to easily and precisely adjust the pressure in the tank.

A photo of the assembled gas gun is shown in Figure 8. While equation 8 relates the striker speed to gas tank pressure, it neglects any losses due to friction or gas expansion; during the system calibration, the relationship between pressure and striker speed will be tabulated to take into account any frictional losses that may occur. In order to tabulate such a relationship, an Ardunio UNO has been configured with two laser emitters and photodiodes in custom 3D printed holders to function as a photogate measuring the striker impact velocity. When the striker passes through each of laser beams in the 3D printed supports, the Arduino takes a time and back calculates the striker velocity from the distance between the beams. The white velocity measurement supports are shown in Figure 8.

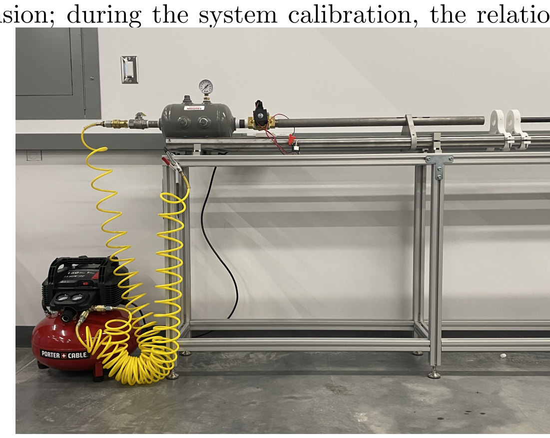

FIG. 8. Picture of Assembled Gas Gun

Data Acquisition

Arguably the most important part of the SHPB system is the data acquisition system (DAQ) since the main goal of the SHPB apparatus is to capture the incedent, transmssion, and reflected waves to back-calculate the applied stress and strain rate in the sample. The DAQ consists of 3 main parts: data collection, signal amplification and processing, and data analysis. A high level schematic of the DAQ system is shown in Figure 9.

The most crucial DAQ component is the device which collects and stores the strain data at a high enough sampling rate. The DAQ must have a sampling rate greater than the nyquist frequency (twice the frequency of the

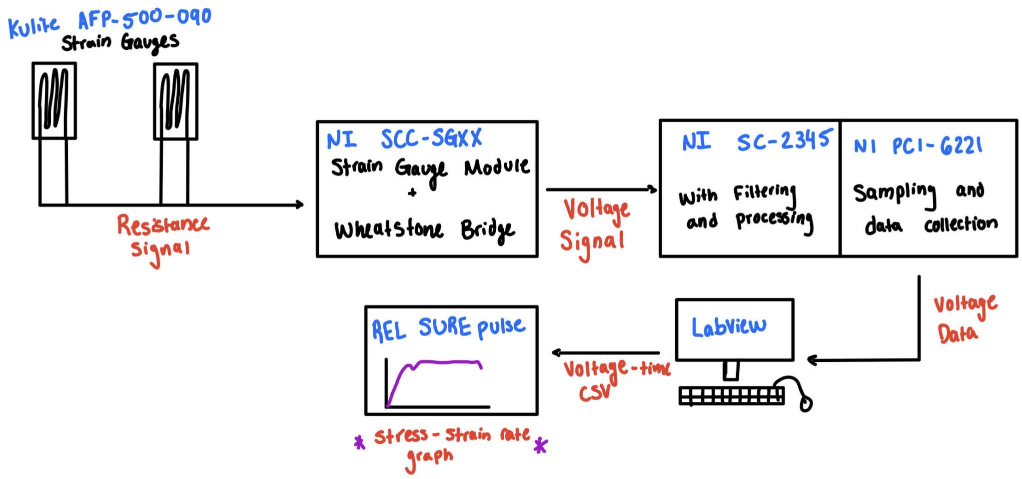

FIG. 9. Schematic of DAQ System

signal being measured) to avoid under sampling and signal aliasing. Additionally, the device must be able to collect data for the maximum full duration of the test. As described above, using Equation 1, the maximum duration of the test will be 196 μs, so the DAQ must be able to collect data at such a high sampling rate for at least that long. Our system will use a National Instruments PCI-6221, which has a sampling rate of 250 kSamples/s and can collect data at this rate for over 1ms. This sampling rate should provide enough resolution in the collected data.

With the sampling device chosen, the next most important components of the DAQ are the high-sensitivity strain gauges. A strain gauge consists of a metal foil attached to a flexible material with a fixed resistance; when a gauge is attached to a member which is stressed, the resistance of the gauge changes as a function of strain. Our system will use Kulite AFP-500-090 linear strain gauges which have a nominal resistance of 500 Ω and can record up to 50,000 microstrain, plenty for our application.

By using the strain gauge as one arm in a balanced full Wheatstone bridge, the change in gauge resistance will affect the voltage across the bridge. Figure 10 shows how the strain gauges will be configured in a Wheatstone bridge to transform the stress signal into a variable voltage. The output voltage of the Wheatstone bridge will be very low, so the output will be amplified as it is being collected by the PCI-6221. A National Instruments strain gauge module, SCC-SGXX, will be used to interface with the strain gauges; This device houses a full Wheatstone bridge for the strain gauge as well as amplification of the output voltage. The output of the strain gauge module will then feed into a National Instruments SC-2345 for signal conditioning to eliminate noise in the data.

Working together, these components will generate a set of voltage-time data from each of the strain gauges as shown above in Figure 3. This data will be collected

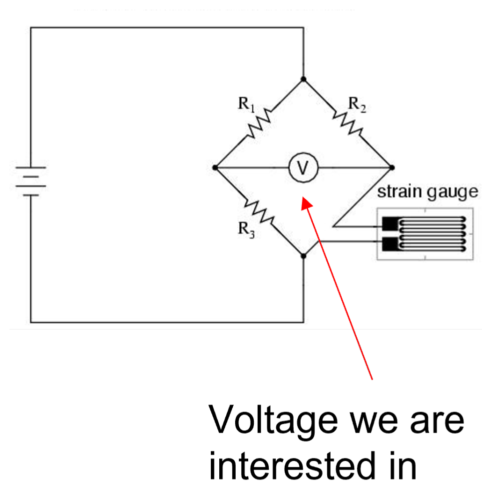

FIG. 10. Strain gauge configured in a wheatstone bridge

by a PC using National Instruments' LabView. The end goal is to determine the stress and strain rate from this voltage data, and this is where the SHPB theory comes in. When the one-dimensional wave condition is satisfied, the following equations can be used to determine the stress and strain rate developed in the sample:

$$\sigma_s(t) = \frac{EA}{A_s}\epsilon_{tra}(t) \tag{9}$$

$$\dot{\epsilon}_s(t) = \frac{-2C}{l_s}\epsilon_{re}(t) \tag{10}$$

where σ_s and $\dot{\epsilon}_s$ are the stress and strain rate developed in the sample, E, A, and C are the elastic modulus, area, and wave speed of the aluminum bars, A_s and l_s are the sample area and length, and ϵ_{tra} and ϵ_{re} are the

TABLE I. Summary of SHPB critical system parameters

Parameter	Value
Bar Material	Al-6061
Bar Lengths	1250 mm
Striker Lengths	250mm, 500mm
Bar Diameter	20mm
Gas Gun Design Pressure	120PSI
Barrel Length	680mm
Max Striker Velocity	15m/s
Momentum Trap Energy Capacity	95.4 J
DAQ Sample Rate	250kS/s
Max Test Duration	196 μs

strain data from the transmitted and reflected waves respectively.

Using Equations 9 and 10 the stress and strain rate developed in the sample can be calculated. REL, a commercial SHPB manufacturer, has an available software called SUREPulse which takes in a CSV of voltage time values, applies the SHPB theory with the relevant parameters, and outputs the desired strain rate plots. We will be using SUREPulse to do this data analysis initially, but may develop a MatLab script to better suit research needs.

REAL SETUP

At this point, all critical system design parameters have been set; Table I summarizes these parameters for the reader.

Models and Simulation

With this ground work in place, a CAD model of the SHPB was created in SolidWorks. Figure 11 shows an image of the CAD model for the system. Making a CAD model helped to understand the scale of the apparatus before assembly, and aided during the design of various system components. A visual representation of the system before ordering parts was crucial to finding and solving system flaws before full development.

In addition to the SolidWorks model, a finite element simulation of the setup was carried out using Abaqus to verify the behavior of the system before assembly. A simplified version of the system was recreated in Abaqus consisting of the incident, transmission, alignment and striker bars as well as the triangular supports. The model was also split in the middle along its axis to limit computation time with a smaller mesh size; this is a valid simplification due to the symmetry of the system. Figure 12 shows a few images of the finite element analysis model. The initial conditions for the transient simulation were that the striker bar was travelling at 15m/s toward the incident bar. The stress wave was evaluated as it propagated down the bars. Figure 12 also shows some results from the simulation. From the analysis, the rigidity of the system and the acceptable usage of the triangular supports were verified. It also demonstrated that with proper alignment, the system will produce a sufficient one-dimensional stress wave to enable the use of SHPB theory as outlined in the DAQ section.

System Assembly

With the CAD model finalized and a sufficient FEA validation of the design, parts were ready to be ordered and the setup was able to be constructed at the Northeastern University Innovation Campus at Burlington. Figure 13 shows a picture of the current state of the assembled system.

A comparison of the actual setup in Figure 13 to the CAD model in Figure 11, reveals a few deviations from

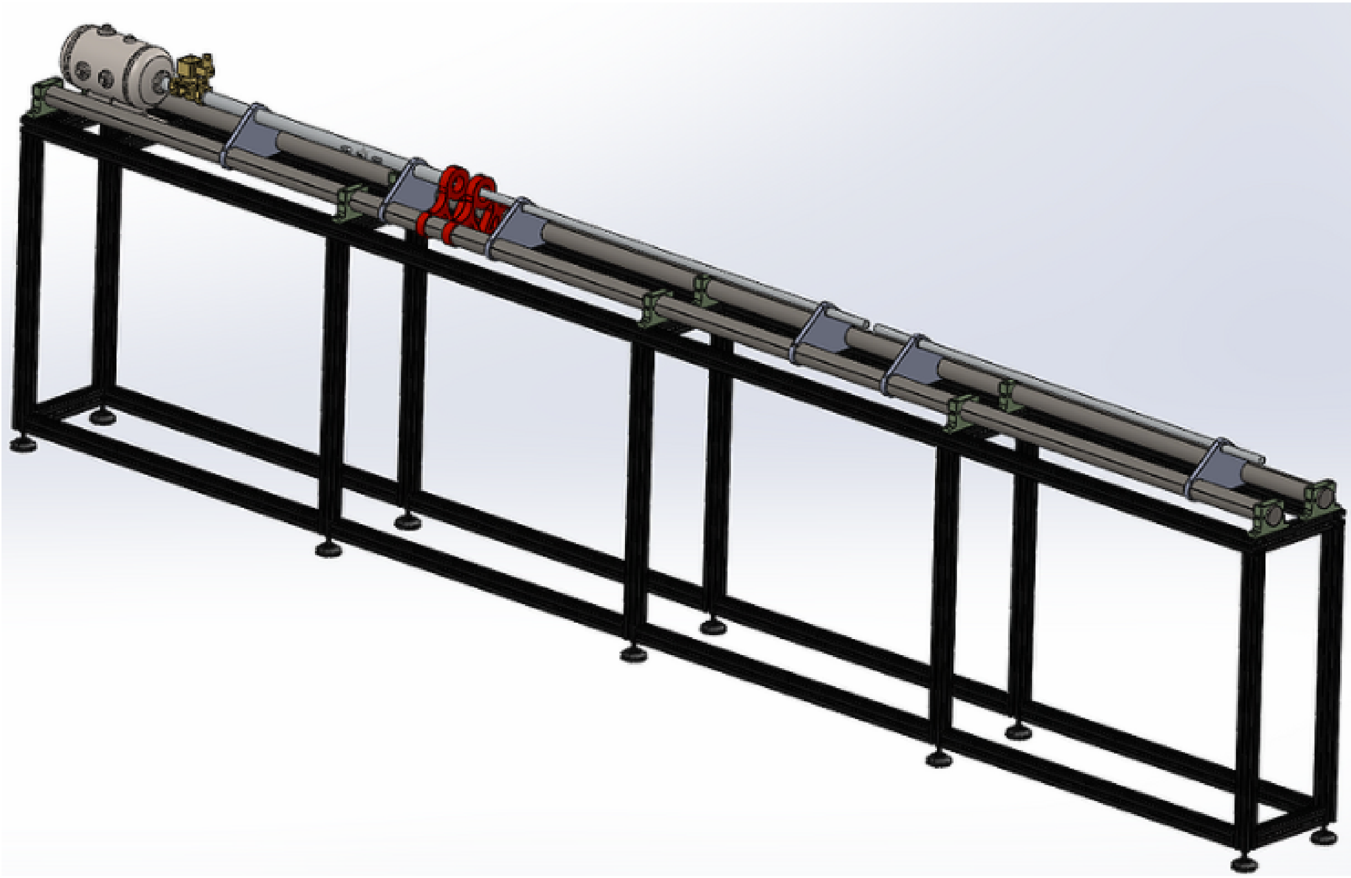

FIG. 11. SolidWorks model of SHPB system

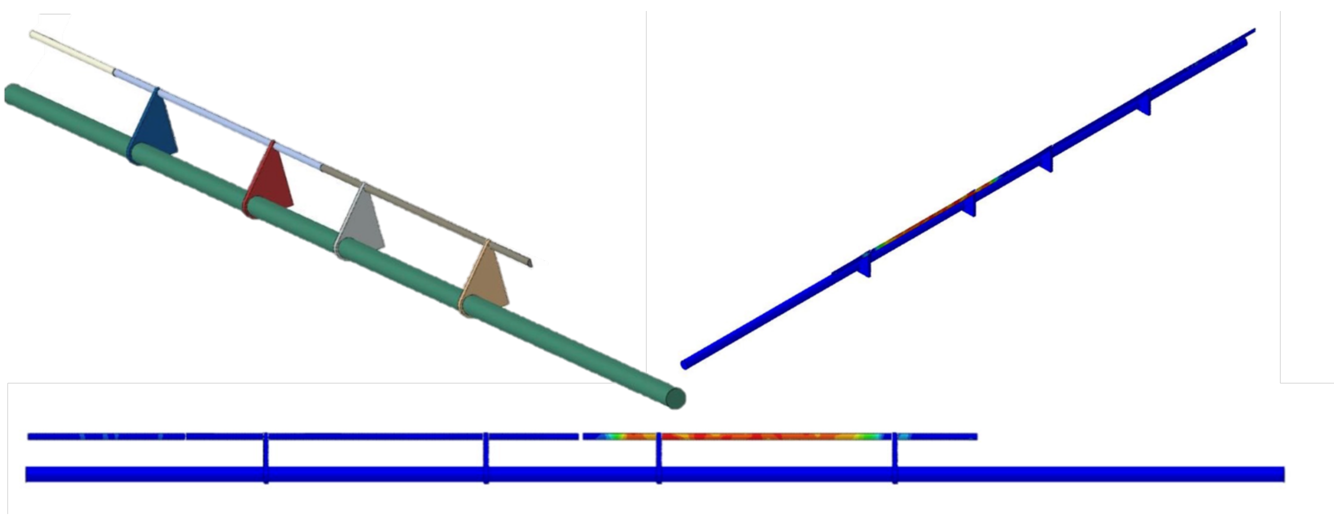

FIG. 12. Model and Results of Abaqus Simulation for designed SHPB system with triangular supports

the initial design. The most significant of these changes is the increased aluminum extrusion and bracing around the base of the system. Upon assembly, and particularly with the addition of the heavy alignment bars, it was deemed that the system was too sensitive to disturbances which could affect the alignment of the bars. As a result these additional braces and plates were added to increase rigidity.

Although not included in the original SolidWorks model, the momentum trap fixture also underwent some changes upon assembly. After running the system, the momentum trap flexed backward when impacted by

FIG. 13. Assembled SHPB system at Burlington

the transmission bar on its original aluminum extrusion mount. Much more aluminum extrusion has been added to secure the momentum trap and ensure robustness of the system.

FUTURE WORK

While the system looks complete, there is still work left to do before this SHPB apparatus can be used for any actual material testing. Right now, the system is assembled: it can accelerate a striker to impact the incident bar, sends a stress wave down the length of the system, and the motion is arrested by a momentum trap. The only thing missing from the current assembly is a calibrated and verified data acquisition system.

Most of the DAQ components to be used have been acquired and proven to be sufficient for our application, they simply need to be configured with the assembly and setup in Labview to enable strain data collection. Additionally, the high sensitivity strain gauges still need to be fit to the bars and configured with the rest of the DAQ. A control box will be created to fire the system, trigger the DAQ, and begin striker velocity measurement simultaneously for ease of operation and data collection.

Once we are able to collect strain data, the system assembly will be complete and validation can begin. First the system will be run without a sample to ensure the one-dimensionality of the induced stress wave. When the incident and transmission bars are touching without a sample in between, there is no impedance mismatch between the bars, so there should be no deviation in the stress wave produced by the striker bar unless the wave is not purely axial. If the strain signal measured by the incident strain gauge is identical to that measured by the transmission strain gauge, then the one-dimensionality is validated; if the signal deviates, the triangular supports will need to be tuned until this condition is satisfied.

During this calibration process, the striker velocity measurement system will be used to generate a regime map detailing the achievable striker impact speeds as a function of gas gun pressure for the various strikers. As mentioned, the true impact speed will deviate from the ideal theory which neglects friction and other losses, so this data will be imperative for system use in the future.

After all of that is complete, the system will then be ready to start being used on polymer samples. A mold will have have to be created to manufacture samples of the proper geometry described above. Then, several polymer samples with already published SHPB data will be synthesized and evaluated using our system. The collected data will be compared to the accepted data and if our system reproduces the data, the system will be fully calibrated, verified, and ready to be used for university research on new materials. A detailed safe operating procedure and an engineering control document will then be written so that others may operate the system properly.

While the system was also designed for the purpose of testing thermoplastic materials at high strain rates, the system design also includes the capability to remove the striker, incident, and transmission bars. This will allow the aluminum bars to be swapped for steel or polymer bars in the future. With identical bar geometry but different bar materials, the system can be adapted for testing on materials with other mechanical impedances like metals or softer polymers. This will require significant additional calibration and verification efforts so at the moment polymer materials and aluminum bars are the focus.

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