Providing Learning Opportunities by Designing a Split Hopkinson Pressure Bar

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Dr. Yuanwei Jin is currently an Associate Professor of Electrical Engineering in the Department of Engineering and Aviation Sciences at the University of Maryland Eastern Shore (UMES). He received his Ph.D. degree in Electrical Engineering from the University of California at Davis in 2003. From 2003 to 2004, he was a Visiting Researcher with the University of California at Santa Cruz. From 2004 to 2008, he was a Postdoctoral Research Fellow, then Project Scientist, with the Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA. From August 2008 to July 2012, he was an Assistant Professor with the Department of Engineering and Aviation Sciences at the University of Maryland Eastern Shore, Princess Anne, MD. From August 2010 to June 2012, he served as the Interim Department Chair.

His research interests are in the general area of signal processing and sensor array processing, with applications in radar/sonar, biomedical imaging, structural health monitoring, and non-intrusive loading monitoring for smart facilities. He received a 2010 Air Force Summer Faculty Fellowship award. He was a recipient of an Earle C. Anthony Fellowship from the University of California at Davis. He is a Senior Member of the IEEE. He holds two U.S. patents. He is affiliated with several IEEE societies, Sigma Xi, SPIE, and ASEE.
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Senior students are always challenged to apply their engineering knowledge and research skills gained from an engineering curriculum toward design and implementation of challenging senior design projects. Split Hopkinson pressure bar is an apparatus that is used to study materials behavior under high speed deformation, where strain rate is very high. Hopkinson bars are usually custom made based on the needs of customers, who are mostly researchers in universities or research labs. In this work, the authors provided learning opportunities for engineering students to design a small size low cost split Hopkinson pressure bar in a form of senior design project. The objectives of this project are to engage a student: 1) to design a well-structured Hopkinson bar by means of fundamentals of mechanics and finite element simulation 2) to build a working prototype of the apparatus for future research activities; and 3) to develop high speed deformation experiments for instructional purposes. The designed Split Hopkinson bar consists of two metallic bars with a specimen placing in between, a striker assembly, an air compressor, an instrumentation and data acquisition system. The experiments for using the split Hopkins pressure bar are conducted as an impact is made by the striker on one of the bars, which generates stress wave through the specimen and the other bar. During the experiments, strain in specimen is determined by measuring strains on the bars using strain gauges mounted on the bars.

The student implemented the fundamentals of mechanics to design the apparatus. The student also built the solid model of the apparatus using CAD software and validated the design by extensive finite element simulation. A working prototype was physically built and tested. Preliminary tests demonstrate that the performance of the apparatus is as desired. In this paper, the authors elaborate on how the student have utilized the extensive engineering knowledge acquired throughout the course to design and develop this Hopkinson pressure bar and thus the educational gains achieved. This work is supported by an NSF’s CMMI (Civil, Mechanical and Manufacturing Innovation) program.

Introduction

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

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

The material properties differ for each material for a low strain rate deformation compared to a high strain rate. Split Hopkinson Pressure Bar is an apparatus that is used for measuring the properties of different specimens with different materials at high Strain Rate \(10^{-1} 10^8 \text{ s}^{-1}\).

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

![Figure 1 - Schematic of Split Hopkinson Pressure Bar (SHPB) Apparatus](image)

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

The objective of this work is to engage an undergraduate engineering student to utilize the fundamentals of mechanics along with Finite Element Simulation to design a small size low-cost Split Hopkinson Pressure Bar for instructional purposes.

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

1- The project aims to improve the ability of the student to design a realistic system and its components under realistic design requirements and constraints.
2- The projects aims to improve the ability of the student to apply fundamental of mathematics, and engineering (such as Dynamics and Mechanics of Materials)
3- The project is to improve the ability of the student to apply modern engineering tools (such as SolidWorks, ABAQUS, Matlab) to analyze and design a realistic system and its components.
4- The project is to improve the student’s hands on skills in fabricating a working prototype of the system.
5- The project aims to improve the ability of the student to design experiments, conduct experiments, collect data, analyze and interpret data.
6- The project aims to improve the student’s written and oral communication skills.

The educational goals of the project correlate closely with most of the ABET student outcomes (a-k), which are widely accepted in engineering education community. These outcomes have introduced and mandated by ABET for engineering programs to ensure the quality of engineering graduates. Projects similar to this project would help engineering educators to cover many student outcomes in senior design classes, which improve the quality of engineering education.

Only one senior level student worked on this project over the course of two semesters under senior design project I and II classes. The student worked in the summer time between the two semesters. The student was mostly funded by an NSF MRI grant during his involvement with the project. It is intended that the project complements the prior works of the other educators in improving senior design classes [5-8].

Nomenclature

\[ F = \text{Force applied by air pressure} \]
\[ P = \text{Air Pressure} \]
\[ L_c = \text{Striker’s cylinder length} \]
\[ A_c = \text{Cross sectional area of striker’s cylinder} \]
\[ m_{st} = \text{Striker projectile mass} \]
\[ V_{st} = \text{Striker projectile velocity at the moment of impact} \]
\[ a_{st} = \text{Acceleration of the striker projectile} \]
\[ L_{st} = \text{Striker projectile length} \]
\[ L_s = \text{length of specimen} \]
\[ \sigma_s = \text{History of specimen stress} \]
\[ \varepsilon_s = \text{History of specimen strain} \]
\[ \dot{\varepsilon}_s = \text{Strain rate in specimen} \]

Problem Statement

The main purpose of this project is to engage an undergraduate engineering student to design and prototype a well-structure Split Hopkinson Pressure Bars (SHPB) apparatus for instructional activities of the department. The apparatus should eventually take measurement of both the strain and stress that a specimen is experienced when subjected to high speed deformation. The apparatus should be designed so that undergraduate engineering students can be exposed to high-speed deformation experiments.
The design needs are as follows:

- The deformation and wave propagation should be uniform and uniaxial so that the strain rate and compressive stress wave could be determined accurately based on the technique introduced by Kolsky.
- The maximum strain rate of $5000 \, s^{-1}$ should be attained by the apparatus.

The design constraints are as follows:

- Due to limitation of the laboratory space, the apparatus size should be limited to 2 meters in length.
- Due to budget limitation, the total cost of the prototype should not exceed $1000.

**Initial Design:**

As shown in Figure 2, the major components of a generic Split Hopkinson Pressure Bar apparatus are as follows:

- **Nitrogen Tank / Compressor** is the pressure source that the striker projectile is provided in order to achieve the velocity and acceleration needed.
- **Pressure regulators** are used to decrease the pressure from the pressure source to a specified pressure for the system.
- **Striker Projectile** is a piece of metal inside a metal cylinder that uses the pressure provided to accelerate and achieve the velocity needed for an impact to the incident bar.
- **Pressure Valves** are used to work as a pressure switch to shut off or turn on the pressure into the striker cylinder.
- **Vacuum Pump** is used to apply vacuum in the striker cylinder in order to bring the projectile back to its initial position after an experiment is completed.
- **Incident and Transmitter Bars** are the two bars that sandwich the specimen in order to characterize the stress and strain that the specimen is undergone.
- **Laser Sensor** is used to detect the position of the striker in order to shut off the pressure valve when needed.

![Figure 2- Schematic of Split Hopkinson Pressure Bar apparatus with pressure system](image-url)
Design Approach

To achieve the objectives of the project, the design of the Split Hopkinson Pressure Bar is to progress in 4 different phases:

- Phase 1: Design of the incident and transmitter bars
- Phase 2: Design for the pressure needed for the system
- Phase 3: Design of the striker assembly that provides the compressive wave
- Phase 4: Select the instrumentation to retrieve appropriate data

Phase 1:
*The purpose of phase one is to design the incident and transmitter bars.*

The main constraint in designing the bars is to select a large Length to Diameter Ratio to ensure uniaxial wave propagation throughout the bars. Additionally, as specified as one of the design constraints, the total length of the apparatus should not exceed 2 m. To stay within the 2 m length constraint, the length of the bars is chosen to be 0.75 m. The diameter of the bars is chosen as 19 mm. The Length to Diameter Ratio of the bars is calculated as 39, which ensures the uniaxiality of the system. Since the length of both the incident bar and transmitter bar are selected as 0.75m, there is only 0.5 m room left to be considered for the lengths of other components to satisfy the size constraint. Thus, the striker assembly length should be selected based on the room left estimated.

Phase 2:
*The purpose of this phase is to determine the pressure needed for the system.*

Figure 3 shows the schematic diagram of the pressure system, which contains pressure source, and striker assembly. The inlet of the striker assembly is attached to the pressure source, which supplies air pressure. The pressurized air coming through the inlet pushes the striker projectile through the striker cylinder. The striker projectile accelerates inside the cylinder until it reaches the end of the cylinder. At this point, the striker projectile impacts the incident bar generating a stress wave, which propagates through the specimen. The stress wave going through the specimen causes high speed deformation in the specimen. The faster the striker projectile impacts the incident bar, the higher the strain rate the specimen undergoes. Thus, the strain rate in the specimen is a function of the striker velocity at the moment of impact. The striker velocity is mainly dependent upon the striker acceleration and the length of the striker cylinder. The striker acceleration is generated by the air pressure supplied by the pressure source. Increasing the pressure increases the striker acceleration leading to higher velocity at the moment of impact, which translates to higher strain rate in the specimen. Thus, the higher the pressure provided at the inlet of the striker assembly, the higher the strain rate in the specimen. It should also be noted that the length of the striker cylinder is an important factor. A longer cylinder provides more distance for the striker projectile to accelerate and reach higher velocity at the moment of impact leading to higher strain rate in the specimen. As mentioned in Phase 1, the length of the striker assembly should be limited to the estimated room left (about 0.5 m). Within this constraint, the purpose of this design phase is to calculate the pressure needed to generate the desired strain rate of $5000 \, S^{-1}$ as specified as one of the design needs.
As mentioned, the pressure at the inlet of the striker assembly generates a force distributed on the surface of the striker projectile. The striker projectile accelerates as a result of this force. Newton’s second law is written for the striker as:

\[ \Sigma F = P A_c = m_{st} a_{st} \quad (1) \]

where \( P \) is the air pressure at the inlet, \( A_c \) is the cross sectional area of the striker cylinder, \( m_{st} \) is the striker projectile mass, and \( a_{st} \) is the acceleration of the striker projectile. Solving for striker acceleration yields

\[ a_{st} = \frac{P A_c}{m_{st}} \quad (2) \]

The striker projectile moves through the entire length of the cylinder before the impact occurs. Assuming a constant acceleration, the velocity of the striker projectile is calculated at the moment of impact, when the striker projectile reaches the end of the cylinder.

\[ V_{st} = \sqrt{2a_{st} L_c} \quad (3) \]

where \( V_{st} \) is the striker projectile velocity at the moment of impact, \( a_{st} \) is the acceleration of the striker projectile, and \( L_c \) is the length of the striker cylinder. Substituting equation (2) into equation (3), the striker velocity at the moment of impact is formulated in terms of the inlet pressure, geometrical characteristics of the striker cylinder and the mass of the striker projectile as

\[ V_{st} = \sqrt{\frac{2 P A_c L_c}{m_{st}}} \quad (4) \]

Rearranging equation (4), the inlet pressure is derived in terms of the velocity of the striker, the mass of the striker and geometrical characteristics of the striker cylinder as
The strain rate in the specimen $\dot{\varepsilon}_s$ is mainly determined by the velocity of the striker projectile $V_{st}$ and the specimen length $L_s$ based on equation (6).

$$\dot{\varepsilon}_s = \frac{V_{st}}{L_s}$$  \hspace{1cm} (6)

Alternatively, equation (6) can be written as

$$V_{st} = \dot{\varepsilon}_s L_s$$  \hspace{1cm} (7)

Substituting $V_{st}$ from equation (7) into equation (5), the inlet pressure $P$ is derived in terms of the strain rate in the specimen $\dot{\varepsilon}_s$ as

$$P = \frac{\dot{\varepsilon}_s^2 L_s^2 m_{st}}{2 A_c L_c}$$  \hspace{1cm} (8)

where $L_s$ is the length of the specimen, $m_{st}$ is the striker projectile mass, $A_c$ is the cross sectional area of the striker cylinder, and $L_c$ is the length of the striker cylinder.

Within the size constraint for the striker assembly length, the length of the striker cylinder $L_c$ is selected as 0.3 m (or 1 ft). The diameter of the cylinder is taken as 23 mm. The cross sectional area of the striker cylinder is calculated based on this diameter. A steel striker projectile in a shape of a step bar is considered. Assuming known dimensions for the striker, the mass of the striker $m_{st}$ is calculated as 0.2 kg. The specimen length $L_s$ is considered to be 5 mm. The only remaining variables in equation (8) are the inlet pressure $P$ and the strain rate in the specimen $\dot{\varepsilon}_s$.

Figure 4 depicts the graph of inlet pressure $P$ versus strain rate in the specimen $\dot{\varepsilon}_s$ plotted based on equation (8). This graph is a means to show what level of pressure is required to generate any specific strain rate in the specimen. As shown on the graph, in order to achieve a desired strain rate of $5000 \, s^{-1}$, a pressure of 75 psi needs to be supplied.
This level of pressure could be provided by any of the two pressure sources Nitrogen Tank or Air Compressor. An air compressor has chosen since it is less costly than a Nitrogen tank. Besides, an air compressor does not need a refill after certain times of usage. Moreover, the air compressor comes with a built-in regulator to adjust the pressure, which makes the system much more affordable. The capacity of the compressor selected is 150 psi.

It should be noted that the length of the striker cylinder $L_c$ could be another design factor besides the inlet pressure $P$. In the case where more space is available, a longer cylinder would lead to higher striker velocity at the moment of impact increasing the strain rate in the specimen. Figure 5 shows the striker velocity $V_{st}$ versus inlet pressure $P$ for different lengths of the striker cylinder $L_c$. As discussed previously, due to the size constraint, the student has chosen 1 ft (or 0.3 m) long cylinder. As depicted in the figure, for such cylinder, a pressure of 75 psi accelerates the striker to a velocity of 25 m/s. This striker velocity corresponds to a strain rate of 5000 $s^{-1}$, which the apparatus is designed for.
Phase 3:  
The purpose of this phase is to design the striker assembly

Figure 6 shows the cross sectional view of the striker assembly. The inlet (1) is attached to the pressure source, which supplies air pressure to the assembly. The air entering through the inlet pushes against the surface of the striker projectile (2). That causes the striker projectile to accelerate along the steel cylinder (3) until it reaches the end of the cylinder. The striker projectile hits the incident bar (5) first with its smaller diameter causing an impact on the incident bar. The lock (4) at the end of the cylinder ensures that the striker does not shoot out from the striker housing. In ideal cases, there would be no impact on the lock, since the striker would always impact the incident bar first causing the striker projectile to decelerate significantly. But the lock is designed as a safety feature for the device.
The first step in design of the striker assembly is to ensure that the selected length of the striker projectile $L_{st}$ does cause any overlapping of wave signals in each bar. The length of the incident bar and the speed of the wave propagation in the bar are used to estimate the maximum possible length of the striker projectile.

The second important step is to make sure that the striker cylinder sustains the internal pressure that is provided by the air compressor to accelerate the striker projectile. As discussed earlier, an internal pressure of 75 psi generates a desired strain rate of $5000 \text{ s}^{-1}$. Since the capacity of the compressor selected is 150 psi, a finite element simulation has been conducted for this pressure considering a load increase factor of 2. The striker cylinder model is built in ABAQUS for the purpose of the simulation. An edge boundary conditions is applied on both ends of the cylinder to constraint the model from moving in x, y, and z directions. An internal pressure of 150 psi (or 1035 MPa) is applied uniformly on the entire inner surface of the cylinder. The stress counter of the simulation is depicted in Figure 7. This FEM simulation indicates that the maximum inner stress in the striker cylinder is below the yield strength for the selected material (cold finished steel). That means the striker cylinder only deforms elastically when the maximum pressure of 150 Psi (1035 MPa) is applied.

![Figure 7-Stress contour of the Striker Cylinder under Internal Pressure using FEM Simulation](image)

The third important step in designing the striker assembly is to ensure that the lock and the striker projectile survive in the rare event when an impact occurs between these components. An FEM simulation is conducted using ABAQUS to verify if the lock and the striker survive after the impact. When a pressure of 150 psi (1035 MPa) is applied on the back of the striker projectile, the striker projectile slides inside the cylinder impacting the cold finished steel lock placed at the end of the cylinder. The solid models of the striker projectile, striker cylinder and lock are built in ABAQUS. An edge boundary conditions is applied on both ends of the cylinder to constraint the cylinder from moving in x, y, and z directions. A contact feature is created between the outer surface of the striker projectile and the inner surface of the cylinder. Another contact feature is created between the impact surfaces on the striker and the lock. The stress counter of the simulation is depicted in Figure 8.
The FEM simulation indicates that as the impact occurs, the maximum stress in the lock is less than the yield strength of the material selected (cold finish steel). That means the cylinder lock only deforms elastically when the maximum pressure of 150 Psi (1035 Mpa) is applied. Similar situation is observed for the striker projectile.

**Phase 4:**

The purpose of this phase is to select the instrumentation to be implemented in the apparatus.

For the purpose of measurement, a National Instrument (NI) PXI data acquisition system is used along with SGD-1.5/120-LY11 strain gages that are mounted on the incident bar and transmitter bar. Labview is used as data acquisition software to collect the data during experimentation. The strain gauges selected are highly accurate for static and dynamic measurement. The strain gauges are also flexible and mechanically strong. They are also operable for broad ranges of temperature. National Instrument (NI) PXI data acquisition system selected is both a high-performance and low-cost deployment platform for different applications. This system is widely used in automotive, aerospace, and defense industries for industrial testing and machine monitoring. The selected instrumentation system also features a National Instrument (NI) 4330 PXI block. This board connects to the strain gauges from one end and to the NI PXI data acquisition system from the other end. The board digitizes the strain history picked up by the strain gauges. Labview software is used to analyze, store and retrieve strain data.

**Design Verification**

The student conducted an FEM simulation using ABAQUS to verify the performance of the apparatus. The specimen is considered to be an Oakwood specimen. The air pressure supplied behind the striker projectile is 75 psi. This air pressure generates the strain rate of $5000 \text{ s}^{-1}$, which the apparatus is designed for. For such pressure, the striker projectile impacts the incident bar with 25 m/s causing high speed deformation. This velocity is considered for FEM simulation of the apparatus.
Figure 9 shows the stress analysis in different components of the split Hopkinson pressure bar at different time frames before and after the high speed impact. The positions of each component at different time frames are also depicted in the figure. The striker projectile creates the stress waves, which passes through the incident bar, and propagates into the specimen. A part of the wave reflects back to the incident bar while the rest continues to propagate into the transmitter bar. As mentioned, the simulation is conducted in ABAQUS with a pre-defined velocity of 25 m/s for the striker projectile. Three contact features are defined in the simulation; the first contact is the contact between the striker projectile and the incident bar; the second contact is between the incident bar and the specimen; and the third is between the specimen and the transmitter bar.

The simulation delivers the output stress history in different components, which has been summarized in Table 1 below.

Table 1- Stress history in different components

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Max/min</th>
<th>Stress (MPa)</th>
<th>Elastic/Plastic deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident Bar</td>
<td>Steel</td>
<td>Max</td>
<td>132.563</td>
<td>Elastic</td>
</tr>
<tr>
<td>Specimen</td>
<td>Oakwood</td>
<td>Max</td>
<td>125.3</td>
<td>Plastic</td>
</tr>
<tr>
<td>Striker projectile</td>
<td>Steel</td>
<td>Max</td>
<td>8.575</td>
<td>Elastic</td>
</tr>
<tr>
<td>Transmitter Bar</td>
<td>Steel</td>
<td>Max</td>
<td>13.227</td>
<td>Elastic</td>
</tr>
</tbody>
</table>
Table 1 includes the maximum stresses in the incident bar, specimen, striker, and transmitter bar. The stresses in incident bar, transmitter bar and striker projectile are lower than the yield strength of steel, which is 517 MPa. That means these parts stay under elastic limit when an impact of 25m/s is applied by the striker. In contrast, the Oakwood specimen undergoes a stress of 125.3 MPa, which is higher than the Oakwood yield strength of 50 MPa. That implies that the specimen deforms plastically. The performance of the designed apparatus is verified since none of the components was deformed plastically with the exception of the specimen as a result of the high speed impact. The plastic deformation of the specimen is based on the design.

**Final Design**

Once the design is verified and finalized, the student completes the solid model assembly of the apparatus using SolidWorks. Figure 10 shows the solid model of the final assembly of the designed Split Hopkinson Pressure Bar. The incident bar and transmitter bar are supported by the bearings mounted on a metallic base, which is placed on a wooden base. The striker assembly is placed inside the wooden block housing shown on the left. The wooden block on the right acts as an absorber to stop the transmitter bar at the end of an experiment.

![Figure 10- Solid Model of the designed Split Hopkinson Pressure Bar](image)

Figure 11 shows the designed split Hopkinson pressure bar attached to the compressor, which provides the air pressure necessary for high speed impact. As depicted, a pressure pipe (hosing) is attached to the striker assembly on the left hand side of the apparatus.

![Figure 11-Solid Model of the Final Assembly](image)
Figure 12 depicts the solid model of the final assembly in an exploded view:

![Solid Model of the Final Assembly in an exploded view](image)

**Estimated Cost**

After the design is finalized, and the solid model of the final assembly is built, the student estimates the cost to fabricate a working prototype of the apparatus. A major fraction of the total cost is associated with materials and supplies needed to be purchased. That includes Husky air compressor, electrical valve, pressure pipe, raw material for metal parts, bearings, strain gages, screws and glue to mount strain gages. A minor fraction of the total cost is dedicated to machine shop and welding jobs. The cost table is presented in Table 2. The total cost is estimated as $822, which is lower than the maximum budget of $1000 specified as a design constraint.

**Table 2 - Cost Table**

<table>
<thead>
<tr>
<th>Item / Service</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Husky 4 Gal 1.5 HP</td>
<td>$170</td>
</tr>
<tr>
<td>Metal Parts</td>
<td>$166</td>
</tr>
<tr>
<td>Metal and Welding Jobs</td>
<td>$140</td>
</tr>
<tr>
<td>Bearing</td>
<td>$80</td>
</tr>
<tr>
<td>Strain Gauges</td>
<td>$49</td>
</tr>
<tr>
<td>Pressure Pipe</td>
<td>$12</td>
</tr>
<tr>
<td>Electrical Valve</td>
<td>$40</td>
</tr>
<tr>
<td>Tools / Parts</td>
<td>$100</td>
</tr>
<tr>
<td>Screws / Glue</td>
<td>$40</td>
</tr>
<tr>
<td>Wood</td>
<td>$25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$822</strong></td>
</tr>
</tbody>
</table>
Prototype Fabrication

After the design is finalized, and the associated cost is estimated, the student starts his efforts to fabricate the prototype. The incident bar and transmitted bar are purchased and cut to the right lengths. The steel base as well as wooden base are purchased and cut to the dimension. The bearings are ordered. The wooden shock absorber is cut to the dimension. The striker assembly needs future efforts to be completed. A steel cylinder is selected as the striker guide. The cylinder fits inside a wooden block that is used as housing for the striker assembly. The housing is mounted on the metal base. The striker projectile is machined as a step rod. A disk shape stop (lock) is welded to the end of the striker cylinder as a safety feature to stop the striker projectile just in case the incident bar is not in place as an experiment is conducted. The components and subassemblies are assembled into a final assembly. The incident bar and transmitter bar are strain gauged. The striker assembly is attached to the pressure valve and air compressor with air pressure pipe. After the prototype is finalized, the apparatus needs to be tested and validated for the desired performance. Figure 13 presents different photographs of the prototype fabricated.

Figure 13 (a) Split Hopkinson Pressure Bar Prototype fabricated

Figure 13 (b) Split Hopkinson Pressure Bar Prototype attached to the Air Compressor
Testing and Validation

After a prototype of the designed apparatus is built, the performance of the prototype needs to be examined. For testing the properties of specific material under high speed deformation using the split Hopkinson pressure bar fabricated, a specimen is placed between the incident and transmitter bar. A pressure is applied through the pressure source (air compressor). Once the valve is opened, the pressurized air pushes the striker causing the striker to accelerate. The striker projectile impacts the incident bar generating stress and strain inside the incident bar. The stress wave propagates along the incident bar reaching the interface of the incident bar and specimen. Some of the stress wave reflects back to the incident bar as a tensile wave. The rest passes through the specimen, where stress and strain are desired to be estimated. The stress wave...
also propagates into the transmitter bar, which accelerates and impacts to the wooden block (shock absorber) mounted at the end of the apparatus. The strain gages mounted on the incident bar and transmitter bar measure strain signals with respect to time over the course of the experiment. The National Instrument (NI) PXI data acquisition system shown in Figure 14 is used to collect the data. The prototype has been tested at different pressures up to 75 psi, which corresponds to 5000 $S^{-1}$ of strain rate in the specimen. The performance of the apparatus has been successful.

![National Instrument (NI) PXI Data Acquisition System](image)

**Figure 14 - National Instrument (NI) PXI Data Acquisition System used for Data Collection**

**Experimental Results**

The experimental data are obtained using LabView program. Figure 15 shows the strain in the incident bar versus time during an experiment. This strain is measured by the strain gauge mounted on the incident bar.

![Waveform Graph](image)

**Figure 15 - Strain in the Incident Bar versus Time during an experiment**
As shown in Figure 15, the stress wave propagation in the incident bar is represented by number 1. The stress wave propagates all the way inside the incident bar until it reaches the specimen surface where some of the wave reflects back as a tensile wave into the incident bar. The tensile wave is represented by number 2 in Figure 15.

![Figure 15](image)

Figure 16- Strain in Transmitter Bar versus Time during an experiment

Figure 16 shows the propagation of the stress wave inside the transmitter bar. The stress wave is represented by number 3 in the figure. Number 4 represents the reflected wave inside the transmitter bar.

As the future work, the strain data collected on the incident bar and transmitter bar will be processed to calculate the stress $\sigma_s$ and the strain $\varepsilon_s$ in the specimen. This data processing will be based on the equations presented in [2]. After processing the data, the stress-strain graph is obtained for the strain rate at which the experiment has been conducted.

**Student Learning Outcomes**

1- The project exposed a student to design process of a real world Split Hopkinson Pressure Bar system with realistic design requirements and design constraints.
2- The student developed a logical 4-phase design approach to design the main components of the Split Hopkinson Pressure Bar system.
3- The student learned how to apply the fundamentals of mechanics to design for the main components such as incident bar, transmitter bar, striker assembly, bearings, and shock absorber.
4- The student learned how to build a solid model of the system, and how to run a finite element simulation to verify the design.
5- The student gained hands-on experience working with different modern math and engineering software such as MATLAB, SolidWorks, ABAQUS, Labview and etc.

6- The student gained valuable hands-on experience fabricating a working prototype of the apparatus designed. That included significant machine shop and welding shop experience.

7- The student gained valuable hands-on experience on how to instrument the apparatus. That included installing strain gauges on the bars, implementing National Instrument PXI data acquisition system and Labview software for data collection.

8- The student had a chance to successfully test and validate the performance of the prototype fabricated.

9- The student conducted high speed deformation experiments and collected valid experimental data.

10- The student improved his oral communication skill by making weekly presentation to the audience of the senior design class and a faculty advisor.

11- The student improved his written communication skill by documenting the design, design verification, prototype fabrication, testing and validation.

12- The student had a chance to improve his project management skills by setting up project plan, time line, budge and cost table and etc.

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

Future Work

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

1- Some of the design requirements may change. For example, the maximum desired strain rate may change to a lower or higher value.

2- Some of the design constrains may change. For instance, the size constraint of the set up may change to a lower or higher value. The cost constraint may also change. More advanced striker can be designed for higher cost.

3- The current setup has been designed for compressive waves. Similar projects may be defined for tensile mode or even torsional mode of deformation.
4- In the current system, after the experimental data are collected, they are processed and analyzed manually by the user. A new project may proceed to automate data processing and analysis.

Conclusions

Solid mechanics and dynamics fundamentals along with the state-of-art FEM simulations have been utilized to design a small-size low-cost Split Hopkinson Pressure Bar for instructional purposes. The FEM investigations have validated the design since none of the apparatus components has experienced plastic deformation as a result of the striker projectile impact while the specimen deforms plastically based on the design. A working prototype of the designed split Hopkinson pressure bar has been fabricated. The performance of the prototype built has been tested and validated as adequate. The cost is well below commercial systems. Valuable levels of knowledge have been gained through this undergraduate design/research project in the areas of solid mechanics, FEM simulations, computational methods, solid modeling, design and fabrication.

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References